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EFFECTS OF VARIABLE TURBINE AREA
ON SUBSONIC CRUISE PERFORMANCE
OF TURBOJETS DESIGNED FOR
SUPERSONIC APPLICATION

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16. Abstract <p>The specific net thrust and specific fuel consumption of simplified turbojet-engine cycles have been calculated for a wide range of design compressor pressure ratio (4 to 30) and design turbine-entrance temperature (2260° R (1255° K) to 3460° R (1922° K)) through a Mach number range from 0 to 3.6. Partial-power performance for engines with both fixed and variable turbine area was determined for Mach numbers from 0 to 1.0.</p> <p>High-pressure-ratio compressors provided significant improvements in specific fuel consumption throughout the Mach number range; however, important losses in specific thrust occurred at the higher speeds. Turbine-area reductions of up to 40 percent resulted in improvements in partial-power minimum specific fuel consumptions of from 10 to 45 percent at subsonic speeds.</p>					
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SUBSONIC CRUISE PERFORMANCE OF TURBOJETS
DESIGNED FOR SUPERSONIC APPLICATION

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SUMMARY

A study of the effects of variable-area turbines on the subsonic partial-power performance of turbojet engines designed for supersonic cruise operation has been conducted for wide ranges of sea-level static design compressor pressure ratio (4 to 30) and maximum turbine-entrance temperature (2260°R (1255°K) to 3460°R (1922°K)). To form a basis for performance comparison of specific net thrust and specific fuel consumption, engines with fixed turbine area were also studied for this range of parameters; in addition, the maximum-power performance of these engines was determined at Mach numbers up to 3.6.

The calculations showed that with reductions in turbine area up to 40 percent of each design value, the partial-power specific fuel consumption was reduced substantially compared with that of the fixed-area engines, particularly for the higher maximum turbine-entrance temperature designs. The variable-area concept provides the maximum thrust advantages of high design turbine temperature along with the advantages of the minimum specific fuel consumption of lower temperatures. Improvements in minimum specific fuel consumption afforded with variable area ranged from about 45 percent to 10 percent at Mach numbers from 0 to 1.

Operation at maximum thrust conditions in the subsonic and transonic speed ranges showed the expected improvement in both specific thrust and specific fuel consumption as compressor pressure ratio was increased at given design temperatures and also the large increase in thrust resulting from higher temperatures. In the high supersonic range, however, only the highest temperature engines produced reasonable thrust. The high-pressure-ratio engines continued to provide improvements in specific fuel consumption but significant relative thrust decrements accompanied the improvements.

INTRODUCTION

Analyses of turbojet engines designed primarily for efficient supersonic cruise flight have shown that their performance at subsonic cruise and loiter flight, from which reserve-fuel requirements are determined, is relatively inefficient. Since the weight of fuel reserves can amount to as much as the revenue payload of a supersonic transport, minimization of this nonrevenue payload becomes of great importance.

This inefficiency at subsonic speeds results from conflicting compressor-pressure-ratio requirements. At high supersonic speeds, the pressure rise desired from the compressor is relatively low since the high overall pressure ratio which is necessary for high cycle and overall propulsion efficiency comes predominately from the high Mach number ram-pressure ratio and efficient compression in the air-intake system. On the other hand, at subsonic to transonic speeds the ram-pressure ratio is relatively low, and the overall cycle pressure ratio which still must be high to obtain good efficiency must be obtained almost entirely from the compressor.

A study of the gas-generator cycle will show that once the design values of compressor pressure ratio and turbine-entrance temperature have been selected, flow choking at the turbine entrance requires the compressor to operate at specific points on the compressor map (match points) and effectively limits the operating compressor pressure ratio. Furthermore, at typical subsonic cruise and loiter conditions, the engine thrust required by aircraft with good aerodynamic efficiency is small compared with the maximum available thrust; thus, the engine is forced to operate at reduced compressor speed to satisfy the flow-match requirements.

The incorporation in engine designs of variable-area primary exhaust nozzles helps eliminate the flow restriction of this engine component on match-point operation, and the introduction of variable-angle compressor stators has allowed shifting of compressor-map characteristics to achieve more efficient component matching and increased stall margin. The addition of afterburners to engines has also brought about some relief to the sizing mismatch of aircraft engines over the flight spectrum by providing large thrust increases at critical acceleration and climb conditions. Such large thrust increases, however, are accompanied by high fuel-usage rate per unit thrust increase, that is, by poor overall propulsion efficiency. The incorporation of these variable components in gas-turbine engines, although bringing about important flexibility of engine operation, still does not eliminate the problem of attaining the highest propulsion efficiency possible over the flight envelope of the supersonic cruise airplane.

Various researchers have suggested that if a variable-area turbine could be incorporated in the engine design, the compressor operating points at partial-power conditions could be established independently of the fixed-turbine-area flow-match requirements.

(See for example, ref. 1.) For engines designed with relatively low compressor pressure ratios for efficient operation at supersonic speeds, the concept of variable turbine area would allow maximizing the compressor pressure ratio at high rotational speeds at all partial-power levels by simultaneous adjustment of the turbine-entrance area and turbine-entrance temperature to provide flow match.

A study of the performance of simplified turbojet cycles with both fixed- and variable-area turbines has been conducted for wide ranges of sea-level static design compressor pressure ratio (4 to 30) and maximum turbine-entrance temperatures (2260°R (1255°K) to 3460°R (1922°K)). The engines with fixed turbine area were studied at maximum nonafterburning thrust operating conditions (maximum turbine-entrance temperature) for a range of Mach number from 0 to 3.6 over a selected altitude flight path. Both fixed and variable-turbine-area designs (reductions of up to 40 percent of design value) were studied at Mach numbers up to 1.0 for a wide range of partial-power settings. The schedule of Mach number and altitude is given in the following table:

Mach number	Altitude	
	ft	m
0	0	0
.4	15 000	4572
.6	25 000	7620
.8	Stratosphere	Stratosphere
↓	↓	↓
3.6	Stratosphere	Stratosphere

The performance of each engine defined by these parameters is presented in terms of the specific net thrust and specific fuel consumption. The compressor characteristics were obtained from a nondimensional performance map. The turbine efficiency was assumed to be constant for all operating conditions. Constancy of corrected turbine-inlet flow was used as the flow-matching parameter to define the various engine-operating lines throughout the study. Exhaust-nozzle-throat area at maximum-power operation was allowed to vary to permit component matching at design turbine-entrance temperature and 100-percent compressor speed.

SYMBOLS AND ABBREVIATION

Symbols

A	area, feet ² (meters ²)
F _n	net thrust, pounds (newtons)
F _n /W ₁	specific net thrust, seconds
M	Mach number
N	rotational speed, percent of design value
N _{corr}	corrected rotational speed, $N/\sqrt{\theta}$, percent
p	pressure, lb/ft ² (N/m ²)
R	gas constant
T	temperature, °Rankine (°Kelvin)
V	velocity, ft/sec (m/sec)
W	weight flow, lb/sec (N/sec)
W _{corr}	corrected weight flow, $\frac{W\sqrt{\theta}}{\delta}$, lb/sec (N/sec)
γ	ratio of specific heats
δ	ratio of total pressure to standard sea-level pressure
η	efficiency
θ	ratio of total temperature to standard sea-level temperature

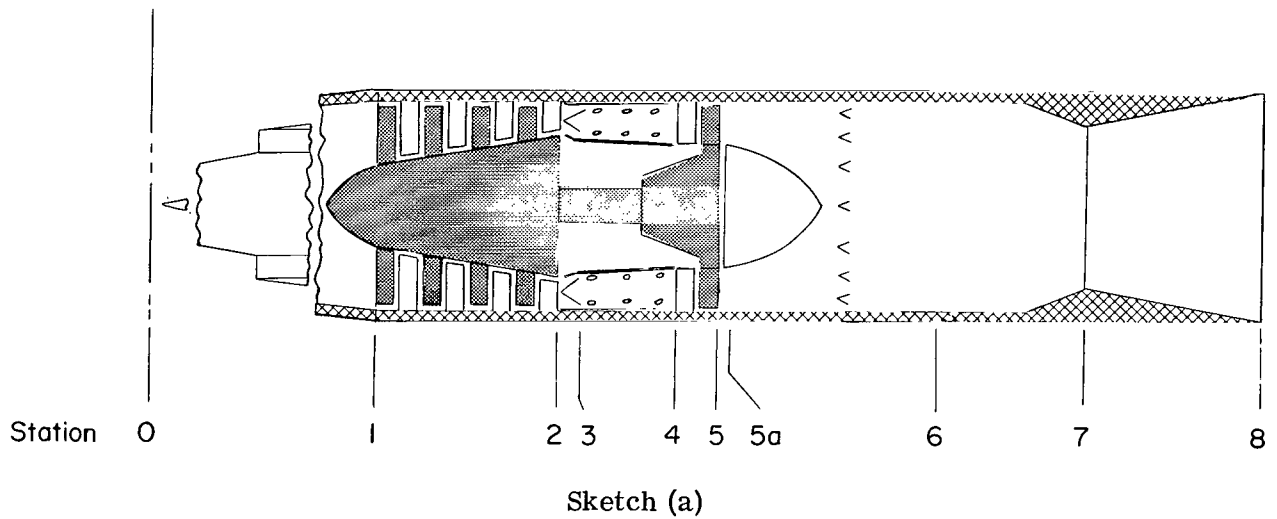
Subscripts:

d	design
max	maximum
min	minimum
sls	sea-level static conditions
t	stagnation or total conditions
0	free-stream station
1	compressor inlet
2	compressor outlet
4	combustor outlet (turbine nozzle entrance)
5	turbine outlet
7	exhaust-nozzle throat
8	exhaust-nozzle exit

Abbreviations

Alt	altitude, feet (meters)
CPR	operating compressor pressure ratio, $p_{t,2}/p_{t,1}$
CPRD	design compressor pressure ratio, $(p_{t,2}/p_{t,1})_d$
SFC	specific fuel consumption, per hour
TET	turbine-entrance stagnation temperature, $^{\circ}\text{Rankine}$ ($^{\circ}\text{Kelvin}$)
TETD	design turbine-entrance stagnation temperature, $^{\circ}\text{Rankine}$ ($^{\circ}\text{Kelvin}$)

The relation of engine stations is presented in sketch (a).



A description of each engine station is presented in the following list:

- | | |
|----|---|
| 0 | free stream |
| 1 | compressor inlet |
| 2 | compressor outlet |
| 3 | combustor inlet |
| 4 | combustor outlet (turbine nozzle entrance) |
| 5 | turbine outlet |
| 5a | turbine cooling air returned to cycle (afterburner inlet) |
| 6 | afterburner outlet |
| 7 | exhaust-nozzle throat |
| 8 | exhaust-nozzle exit |

PERFORMANCE-COMPUTATION PROCEDURES

The computer program used in this study was developed at the Langley Research Center. This program calculates design-point-cycle performance and then uses the computed value of turbine-entrance corrected flow at design $\left((W_4 \sqrt{\theta_4} / \delta_4)_d \right)$ to define, by flow matching, all possible operating points of a given design cycle through a desired Mach number, altitude, and power-level range. The program conducts a step-by-step thermodynamic progression from the undisturbed free-stream condition, to the air intake, through the individual engine components, to the exhaust nozzle. With input to the program of the parameters listed in table I, the program will compute the performance parameters presented in the paper. The nondissociated thermodynamic properties of gases from reference 2 were used in the flow-process calculation. The present study uses the combustion-products tables for a fuel with a hydrogen-carbon ratio of 2 to simulate JP-4 jet-fuel performance.

The nondimensionalized compressor-map characteristics shown in figure 1 were used for all engine designs to retain the parametric identity of the study to the maximum degree possible. Each design-point value of compressor pressure ratio CPRD was established on the map, as shown by the target symbol in figure 1(a), at a point along the 100-percent corrected-speed curve (N_{corr}) , 10 percent of CPRD below the surge value. Off-design compressor-operating points were established by iteration along constant corrected-speed lines until the resulting turbine-entrance corrected flow was matched with the design value; off-design corrected speed was defined by Mach number, altitude, and engine desired-power level.

Definition of operating points by turbine-corrected flow match was required because a map of turbine work and flow characteristics was not included in the program. The quantities that could compromise constant, corrected turbine-entrance flow as the matching parameter are (1) turbine-entrance Mach number less than unity, (2) unknown changes in effective turbine-entrance flow area, and (3) variation in γ_4 and the gas constant R_4 due to changes in turbine-entrance temperature and gas constituency from the design values. Only condition (3) was considered to have important influences; examination of the effects of γ_4 and R_4 variations from design indicated a maximum variation in corrected flow of less than 2 percent of design value when TET was varied from high values at design to very low values at off-design partial power. The variation in compressor corrected inlet flow with Mach number and associated altitude resulting from the present flow-match procedure is presented in figure 2 for the range of conditions studied.

Control of the operating modes of any fixed-turbine-area engine can be accomplished by giving values to two and solving for the third of the following parameters: compressor

physical rotational speed, turbine-entrance temperature, and exhaust-nozzle-throat area. For maximum power at all off-design conditions, compressor rotational speed was set at 100 percent of design, turbine-entrance temperature was set at a design value, and the required nozzle-throat area was calculated. Partial power was defined by a schedule of compressor rotational speed and ratio of nozzle-throat area to maximum-power throat area. (See fig. 3.) Engine control specified in this manner required computer-program loops to satisfy flow matching at both the turbine entrance and nozzle throat by varying turbine-entrance temperature.

Alteration to the computer-program logic to provide for the concept of variable turbine area was quite simple. Upon solution of the compressor-turbine operating point required by flow matching at maximum power, the compressor-map operating point was held in computer memory. The turbine-entrance temperature was reduced for lower than maximum power, the turbine-entrance area was reduced to maintain constant corrected turbine-entrance flow and the exhaust-nozzle-throat area required to pass the internal flow was calculated. The program recognizes a maximum variation in turbine area. To solve for this limit, iteration of turbine-entrance temperature and area is conducted until the limiting input area value is obtained.

The present study was conducted with the air-inlet total-pressure recovery schedule with Mach number shown in figure 4. This schedule is considered typical of fully variable internal-external compression inlets. The exhaust nozzle was assumed to fully expand the internal flow to ambient pressure with a gross-thrust coefficient of 0.985. The schedule for controlling partial-power engine operation (fig. 3) is similar to that for a recent turbojet designed for supersonic speeds.

RESULTS AND DISCUSSION

Fixed Turbine-Entrance Area

Maximum-power performance.- Results for specific net thrusts (F_n/W_1) and specific fuel consumption (SFC) at maximum power (design turbine-entrance temperature, TETD) are presented in figures 5 to 7 for the range of Mach numbers from 0 to 3.6. The data are plotted for constant values of sea-level static design compressor pressure ratio (CPRD) and maximum turbine-entrance temperature so that the influence of these parameters on performance can be traced through the speed range. Only the TETD values listed are constant throughout the speed range; the actual operating compressor pressure ratio at each condition is the particular value resulting from the flow-match process.

The sea-level static performance (fig. 5) shows the expected strong effect of increasing CPRD and TETD on both thrust and SFC. The improvement in thrust at constant TETD was due entirely to the higher exhaust-nozzle pressure ratio $p_{t,8}/p_0$

(fig. 5(b)) since the exhaust-nozzle temperature $T_{t,8}$ continually decreased with increasing CPRD. An important point to note is that minimum SFC and maximum specific thrust are never simultaneously attainable. At any given temperature, there is a pressure ratio beyond which further increases in pressure ratio will produce decreases in specific net thrust.

Increases in Mach number brought about reductions in F_n/W_1 and increases in SFC. (See fig. 6.) At the higher supersonic speeds, only the highest temperature engines produced reasonable thrust levels. Here again, the high-pressure-ratio engines provide significantly lower SFC but now at greatly reduced F_n/W_1 . This point is perhaps better shown in figure 7, where all Mach numbers and CPRD values are grouped together at each TETD value.

It is beyond the scope of this paper to analyze the relative effects of SFC improvements and thrust degradation since for each particular airplane and its mission, the trade-off in engine size, weight, and fuel consumption is required for such an analysis. Some insight into the relative effects due to the increase in CPRD, however, can be gained by the comparisons of figure 8, where performance data are referenced to an engine with a design compressor pressure of 4. At subsonic speeds, thrust increases and SFC reductions of nearly 20 percent and greater than 30 percent, respectively, result from CPRD increases. As Mach number increased, however, the thrust gains deteriorated rapidly. In fact, at Mach 3.6 (fig. 8(g)), a reduction in SFC of about 16 percent was accompanied by a thrust decrease of about 40 percent. The lower temperature engines at this condition produced much lower thrust with either no SFC reduction or with SFC increases at the higher CPRD values. It appears obvious from these comparisons that if it is desirable to minimize SFC at higher Mach numbers, and certainly this would be required for long-range cruise airplanes, the accompanying increase in engine size (airflow) and weight needed to provide the required engine thrust must be traded relative to the possible SFC reductions.

Trade-off studies to provide the optimum engine would involve not only the supersonic cruise performance but also the engine performance throughout the entire flight spectrum: take-off and landing, acceleration and climb to the initial cruise altitude, and the subsonic cruise and loiter required for reserve-fuel considerations. Of particular concern here are the subsonic conditions, where engines are operated at much less than rated power and the SFC performance has important effects on the fuel-reserve requirements. Recent supersonic-transport exercises have shown that with present requirements fuel reserves can amount to more than the revenue payload. The desirability of minimizing partial-power SFC is obvious.

Partial-power performance.- The partial-power performance of several of the study engine designs is presented in figures 9 to 12 for Mach numbers from 0 to 1.0. The

performance data for each CPRD engine at the several TETD values are grouped in each figure; performance data for the variable-area turbine (which will be discussed later) at the same CPRD value are also plotted in each figure. The maximum-thrust point in each figure (the solid symbols) is identical to the maximum thrust point in the previous figures at corresponding conditions. Each data point, after the first partial-power point of the fixed-turbine-area engines, represents an incremental reduction in rotational speed of from 2.5 to 5 percent.

All these partial-power curves show the characteristic reduction in SFC and F_n/W_1 as rotational speed was initially reduced from the maximum value. With further decreases in rotational speed, the SFC reached a minimum value and then increased rapidly for relatively small changes in thrust. The highest rate of SFC increase was experienced by the lowest CPRD engines. Examination of the data showed that the cycle efficiency for these engines, already low because of the low cycle pressure at design, deteriorated far more rapidly with power reduction than that for the higher CPRD engines. This trend occurred because the continuing improvement in propulsive efficiency with reductions in thrust could not maintain the initial increase in overall propulsion efficiency (reduction in SFC).

The four maximum turbine-entrance temperatures studied for each CPRD engine produced a family of performance curves for which the minimum SFC value increased significantly with increasing TETD. Here again, the lowest CPRD engine had the greatest increase in minimum SFC for higher design turbine-entrance temperatures. It is interesting to note that the rise in minimum SFC with increases in TETD was substantially less than that at the maximum-thrust condition of each engine. Another interesting result of these data is the relatively small variation in specific thrust at minimum SFC with increases in TETD even though the maximum specific thrust values for each engine increased greatly with higher temperature.

A correlation of the minimum SFC values from the preceding figures is presented in figure 13 as a function of design compressor pressure ratio. The very significant improvements in SFC afforded by higher CPRD are quite evident for all subsonic conditions; maximum reductions in SFC of nearly 50 percent were produced by an increase in CPRD of from 4 to 30 for the range of design turbine-entrance temperatures. In fact, doubling CPRD from 4 to 8 provided more than one-half the total improvement in minimum SFC. It is apparent from these curves that increases in CPRD beyond those presented would gain very little in minimum SFC. Increases in TETD and increases in Mach number at given TETD values produced higher minimum values of SFC. The data also show, however, that in the lower pressure-ratio range, constant values of minimum SFC can be obtained at higher TETD with increases in CPRD. Thus, the advantage of higher maximum thrust afforded by high TETD can be realized without sacrifice in minimum SFC.

Variable Turbine-Entrance Area

Partial-power performance.- Specific net thrust and specific fuel consumption for engines with variable-turbine areas are presented in figures 9 to 12 at the same Mach numbers and design values of CPRD and TETD as for the engines with fixed turbine area. The ticked symbols and numbers above the symbols correspond to a 40-percent turbine-area reduction for each design turbine-entrance temperature indicated. Numbers missing from the symbols on several plots indicate that the minimum-area point for that particular TETD value was not attained prior to the minimum nozzle-pressure-ratio cut-off point programed in the computer $\left((p_{t,8}/p_0)_{\min} = 1.025\right)$ or the point is simply off the figure scale. The single performance curve at each CPRD value for all TETD values studied resulted because the compressor operating point for all variable-turbine-area engines was fixed at 100-percent rotational speed, and this operating point corresponds to the same operating point as the fixed-turbine-area engines at maximum thrust. Since all other engine-component efficiencies and pressure losses were held at fixed values, comparisons of the several curves defines directly the effect of fixed compressor operating point on partial-power performance.

For the lowest CPRD studied (fig. 9) variable turbine-entrance area provided very large reductions in minimum SFC compared with those of the fixed-area engines and also reduced the specific net thrust at which minimum SFC occurred. The effect of increasing subsonic Mach number was to reduce the SFC advantage of variable turbine area; but even at the highest Mach number of 1.0, the smallest minimum SFC improvement was about 9 percent. The principal reason for the SFC advantage with variable turbine area is that the highest cycle pressure consistent with the CPRD value was maintained throughout the partial-power range and hence the relatively sharp decrease in cycle efficiency of the fixed-area engines with power reductions did not occur. The ticked symbols show that the 40-percent-area reduction is sufficient to provide more than a 3-to-1 range in partial-power thrust at constant rotational speed. Further reductions in turbine area from design would, of course, provide greater ranges in partial-power thrust or, as discussed earlier, a schedule of an exhaust-nozzle throat area and rotational speed control in addition to variable turbine area could provide an even greater range of partial-power thrust.

With increases in CPRD, the improvement in minimum SFC resulting from variable turbine area began to decrease. (See figs. 10 to 13.) As Mach number was increased from 0 to 1, a minimum SFC crossover point was reached for the fixed and variable-turbine-area engines. Beyond this CPRD crossover point, minimum SFC for the variable-turbine-area engines was greater than that for the fixed-area engines even though the compressor pressure ratio was maximized over the entire partial-power range. This increase can be explained by figure 1(b). It can be seen that the efficiency for this

particular compressor is maximum at corrected speeds between 75 to 95 percent. If the variable-area engine is operating at 100-percent rotational speed at a Mach number of 0.8 in the stratosphere ($N_{\text{corr}} = 108.5$ percent), for example, the compressor efficiency would be from 5 to 7 percent lower than for the comparable fixed-area engine operating at lower rotational-speed partial-power points. Such reductions in efficiency can offset the influence of relatively small gains in cycle pressure on overall engine-propulsion efficiency, particularly when the cycle pressure is already high. The advantages of variable turbine area, however, are still quite apparent even for the highest CPRD engine studied in that the minimum SFC and corresponding specific net thrust were considerably lower than those for the fixed-area engine at the highest TETD. (See fig. 12.)

The overall advantage of the use of a variable-turbine-area engine is that it permits the higher maximum thrust provided by higher design turbine-entrance temperature and at the same time allows the obvious advantages of lower TETD values on minimum SFC. These results can be seen from figure 14 where the increase in maximum specific net thrust of a 3460°R (1922°K) design-temperature engine compared with that of a 2260°R (1255°K) design-temperature engine is plotted against the change in minimum SFC of the same designs for engines with both fixed and variable turbine area. The data are presented for the range of CPRD study values for sea-level static and several subsonic conditions.

The 1200°R (667°K) increase in TETD produced increases in maximum specific thrust of from about 45 to 90 percent for fixed- and variable-area designs. For the fixed-turbine-area engines, this thrust increase was accompanied by a minimum SFC increase ranging from about 13 to 27 percent compared with the 2260°R (1255°R) design-temperature engine. The variable-turbine-area design, on the other hand, provided the same thrust advantages and allowed minimum SFC values to be achieved that were 20 percent below to 5 percent above those of the comparable low-temperature fixed-area designs. Thus, the variable-turbine-area engines, by virtue of better pressure-temperature matching, can achieve improvements in minimum SFC varying from about 10 percent to 45 percent compared with the higher TETD fixed-area engines.

Effect of turbine-efficiency variation. - Introduction of the variable-turbine-area concept into turbine-engine design would require solutions to the specific problems of mechanical design and fabrication of movable parts. An important aerodynamic problem is the influence of variable turbine area on turbine-efficiency levels at design and off-design point operation. Although the present study did not include a turbine-performance map for the cycle calculations, the computer program did have provisions for varying turbine-efficiency input to determine the effects of turbine-efficiency variations on overall engine performance.

The results of several computer runs in which turbine polytropic efficiency was decreased by 5 percent are presented in figure 15. The engine performance presented for variable-turbine-area engines encompasses the subsonic speeds investigated as well as the range of CPRD values. The data show that a reduction in efficiency from 90 to 85 percent produced increases in SFC and reductions in net thrust everywhere along the partial-power curves. The performance losses amounted to about 1 percent in both thrust and SFC at maximum power for the range of conditions studied with performance losses increasing as the engine power level was reduced. In the thrust range near minimum SFC, the effect of the turbine-efficiency changes on SFC was much more pronounced. For sea-level static conditions, the 5-percent turbine-efficiency reduction produced increases in minimum SFC of about 10 percent for the range of CPRD values. Increases in Mach number to a typical subsonic cruise value of 0.8 approximately halved the effect of this particular turbine-efficiency change on minimum SFC.

By referring to figures 13 and 14, it can be seen that even with the SFC increase produced by a 5-percent reduction in turbine efficiency, the variable-turbine-area concept continues to offer the possibility of lower minimum SFC throughout the speed range studied compared with that of the fixed-turbine-area engines; the advantages continue to be greater for the low CPRD engines. If implementation of variable-area turbines were to be accomplished at lesser or greater costs in turbine efficiency, minimum SFC would be affected accordingly.

CONCLUDING REMARKS

A study of the effects of variable-area turbines on the subsonic partial-power performance of turbojet engines designed for supersonic cruise operation has been conducted. The specific-net-thrust and specific-fuel-consumption performance of simplified turbojet-engine cycles have been calculated for wide ranges of compressor design pressure ratio (4 to 30) and design turbine-entrance temperature (2260°R (1255°K) to 3460°R (1922°K)) through a Mach number range from 0 to 3.6. Partial-power performance for both fixed- and variable-turbine-area engines was determined for Mach numbers from 0 to 1.0.

The performance data show the expected large improvement in specific fuel consumption and net thrust with increases in design compressor pressure ratio at given turbine-entrance temperatures for subsonic and low supersonic speeds. With increases in speed to the high supersonic range, only the highest temperature engines produced reasonable net thrust throughout the compressor-pressure-ratio range. The effect of increasing compressor pressure ratio at maximum turbine-entrance temperature for a Mach number of 3.6 was to provide a maximum reduction in specific fuel consumption

of about 16 percent which was accompanied by a decrease in specific net thrust of greater than 40 percent.

At subsonic speeds and at partial-power operation, all engines exhibited reductions in specific fuel consumption as thrust was decreased from the maximum value; the engines with the lowest design turbine-entrance temperature and highest pressure ratios had the lowest minimum specific fuel consumption. At thrust levels below the minimum specific-fuel-consumption values, specific fuel consumption increased greatly because of the rapid decay in overall engine pressure ratio and consequent reduction in engine cycle efficiency.

Varying the turbine-entrance area to provide flow match at high pressure ratio consistent with the compressor design value of pressure ratio (100-percent rotational speed) provided significant improvements in specific fuel consumption at all partial-power thrust for engines with high design turbine-entrance temperatures. The greatest advantage of variable area occurred for the low-pressure-ratio engines where engine cycle efficiency was already low at design. Minimum specific-fuel-consumption improvements for the variable-turbine-area engines ranged from about 45 to 10 percent for Mach numbers from 0 to 1.0 at comparable turbine-entrance-temperature designs; these improvements occur if turbine efficiency is not affected adversely by the incorporation of a variable area design. An arbitrary reduction in turbine efficiency of 5 percent reduced the variable-turbine-area gains in minimum specific fuel consumption by about 10 percent.

Langley Research Center,

National Aeronautics and Space Administration,

Hampton, Va., July 21, 1970.

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TABLE I.- PROGRAM INPUT

Flight condition (standard day):

Altitude	0 to stratosphere
Mach number	0 to 3.6
Power setting	Maximum and partial

Compressor:

Design pressure ratio	4 to 30
Design efficiency	0.875
Maximum rotational speed, percent	100

Combustor:

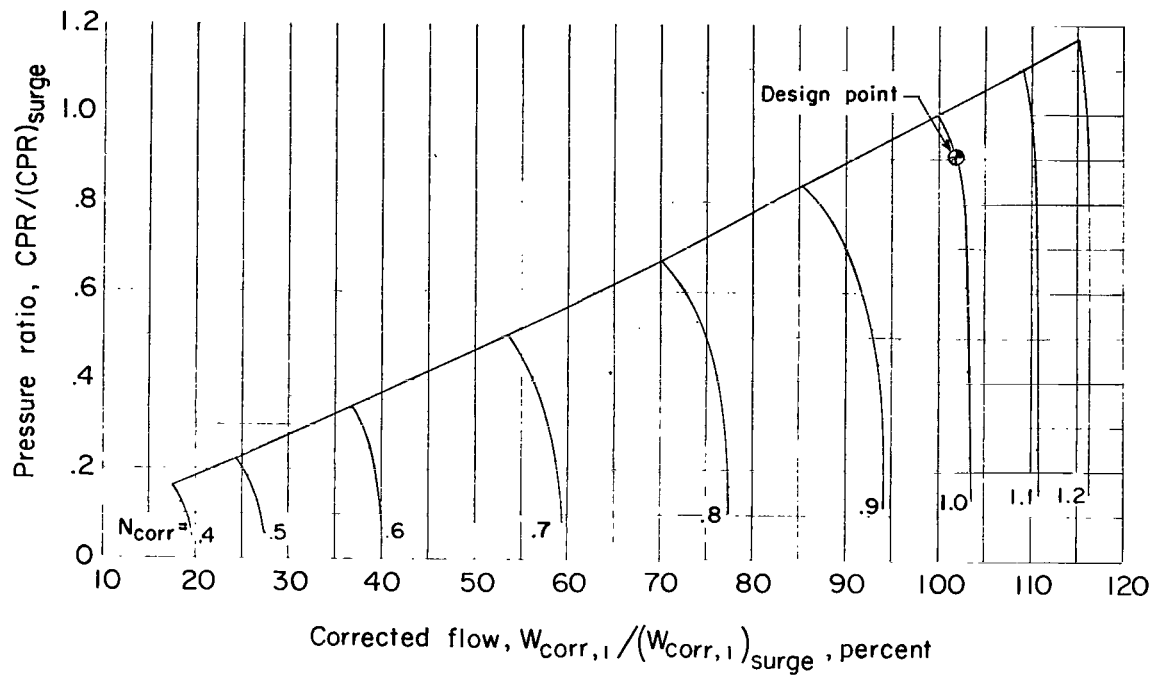
Maximum design turbine-entrance temperatures, $^{\circ}\text{R}$ ($^{\circ}\text{K}$)	2260 (1255) to 3460 (1922)
Combustion efficiency	0.98
Design combustor total-pressure ratio	0.95
Fuel sensible energy, Btu/lb (MJ/kg)	1600 (3.72)
Fuel total enthalpy, Btu/lb (MJ/kg)	20 000 (46.49)
Initial liquid-fuel temperature, $^{\circ}\text{R}$ ($^{\circ}\text{K}$)	350 (194.4)

Turbine:

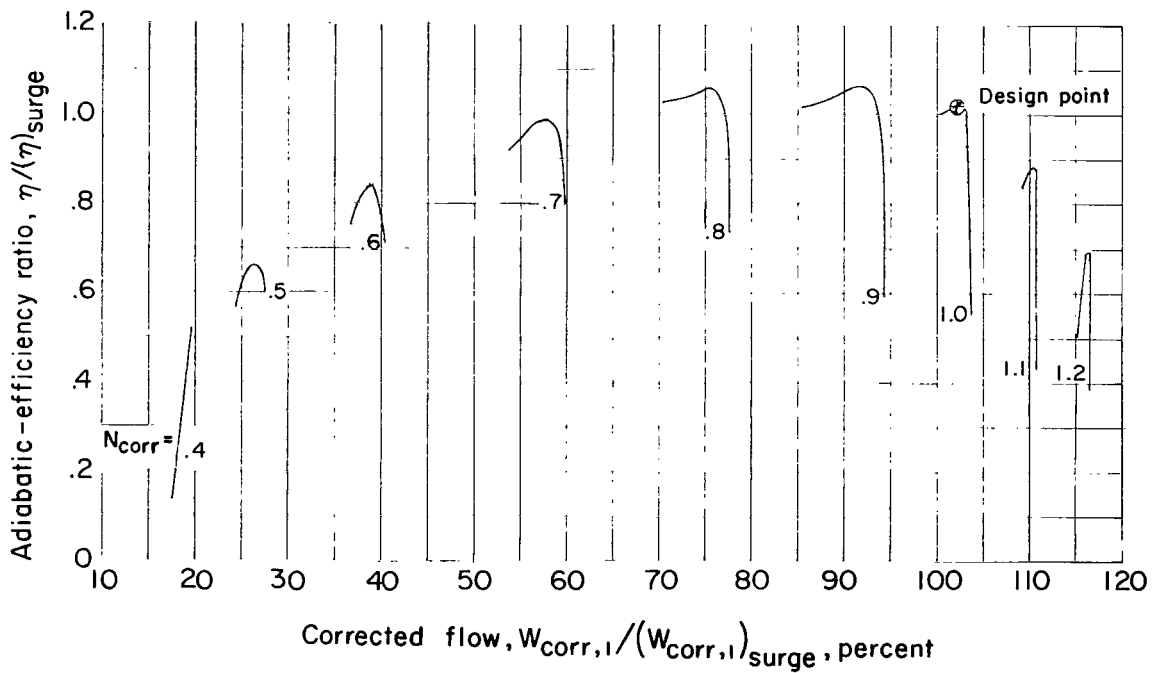
Polytropic efficiency	0.90
Cooling air, percent	0

Nozzle:

Tailpipe total-pressure ratio	0.95
Gross thrust coefficient	0.985
Static-pressure ratio	1.0



(a) Pressure ratio as a function of corrected flow.



(b) Efficiency as a function of corrected flow.

Figure 1.- Nondimensional compressor map.

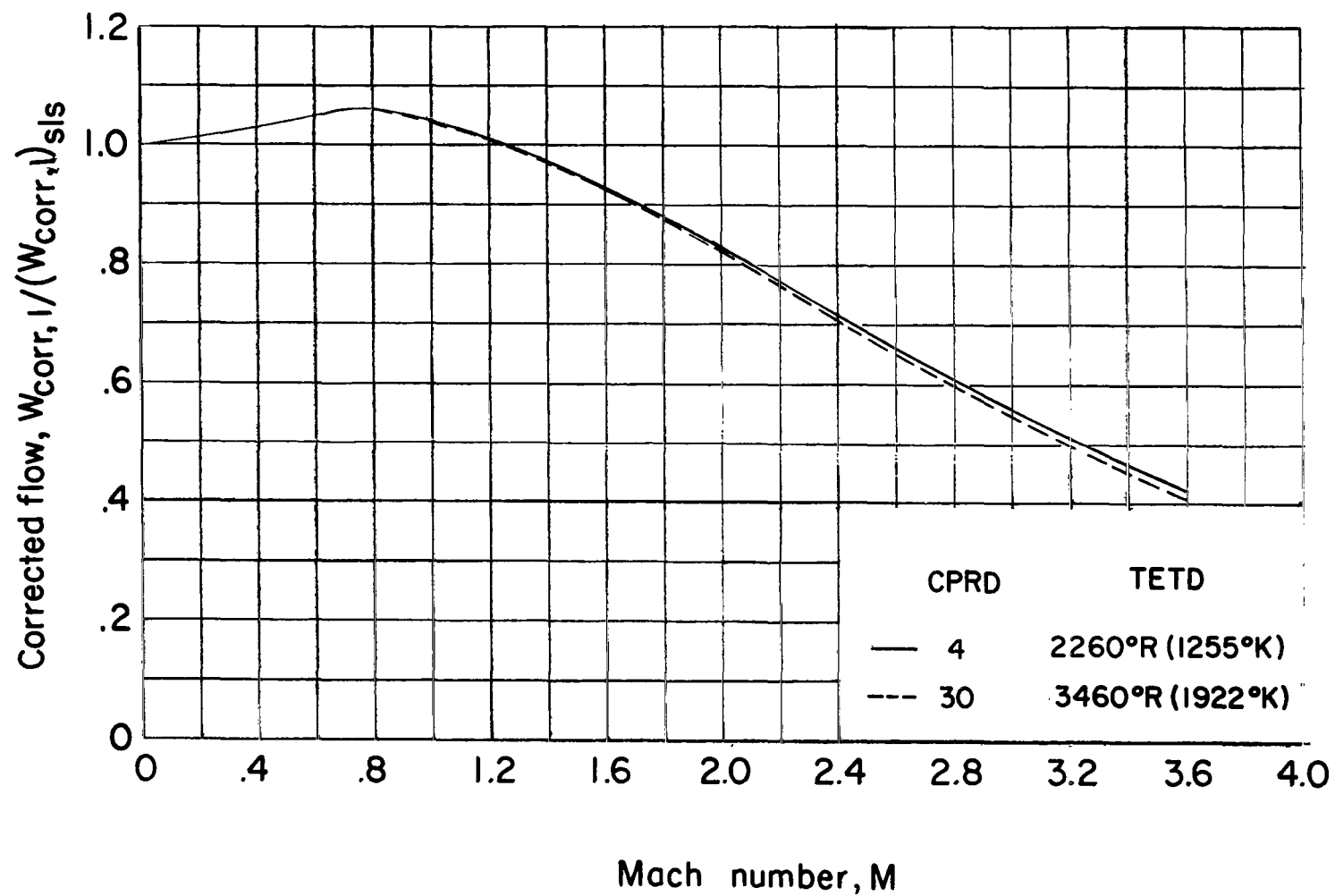


Figure 2.- Variation of compressor corrected inlet flow with Mach number for range of design engines.

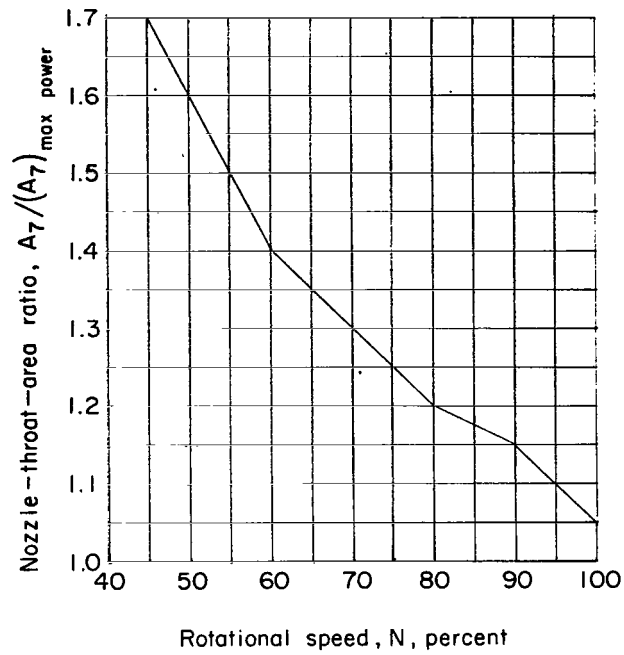


Figure 3.- Schedule of ratio of exhaust-nozzle-throat area used for partial-power control.

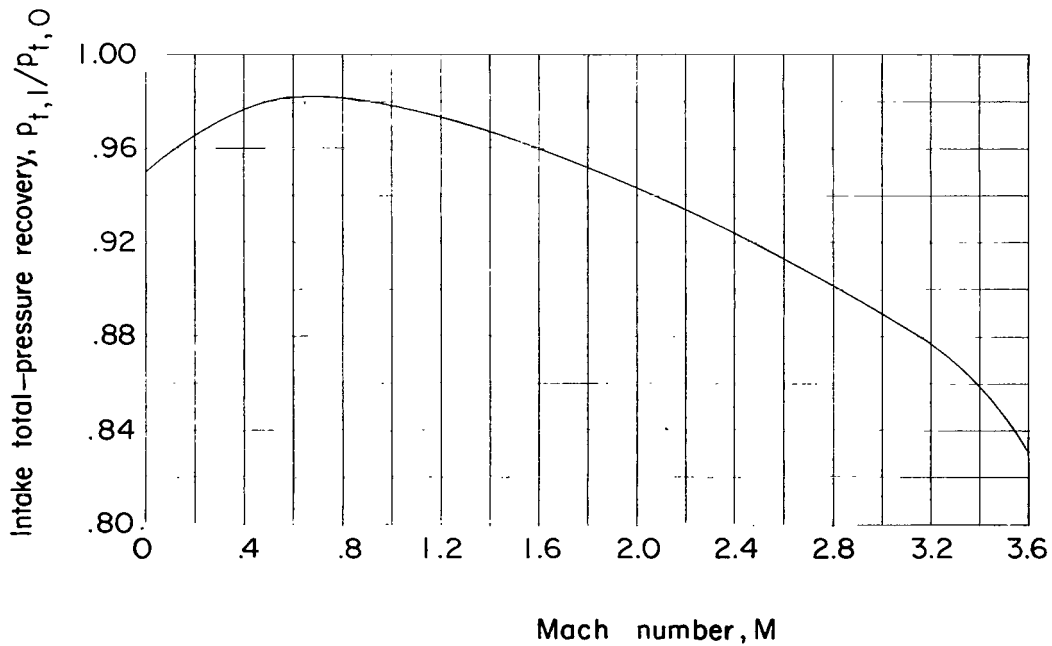
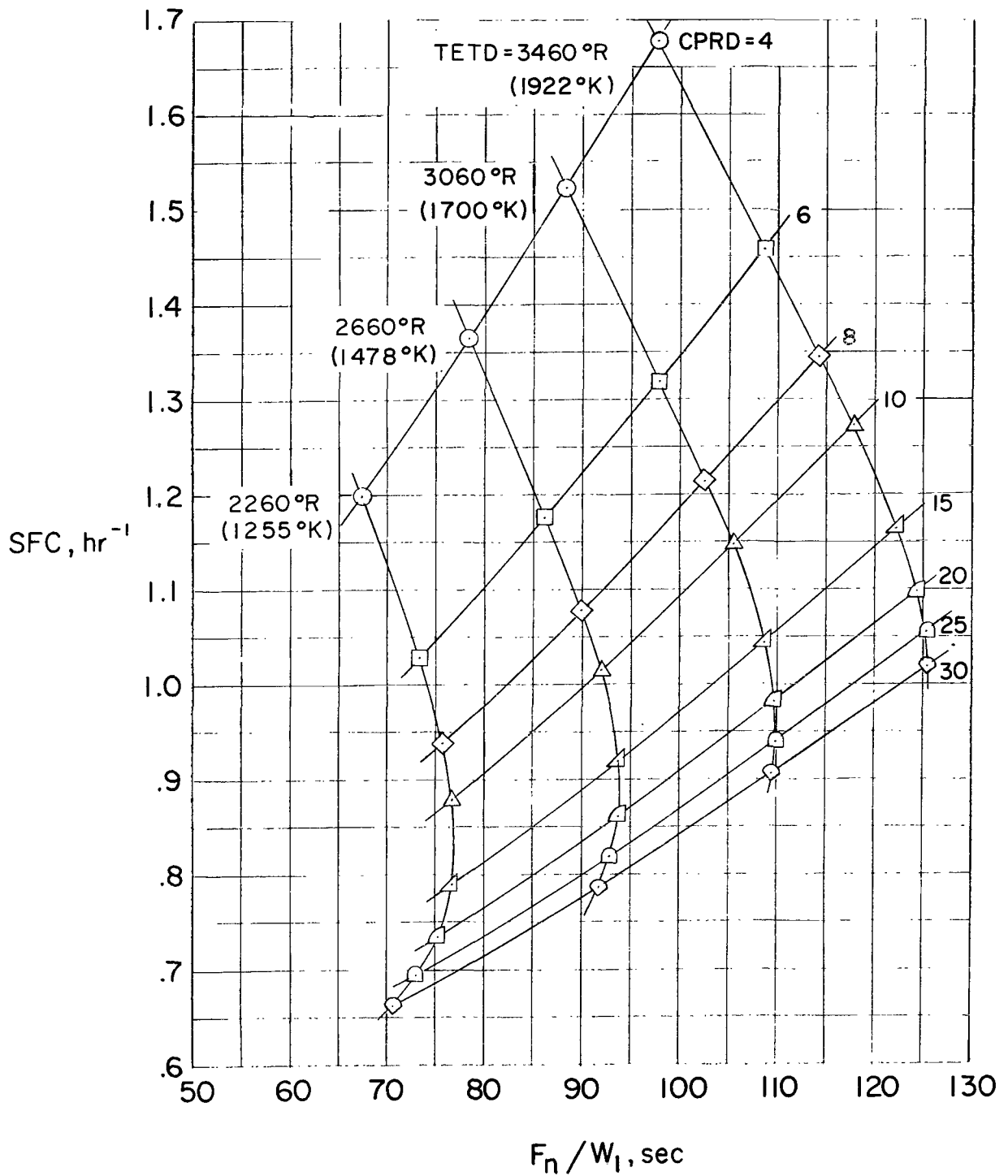
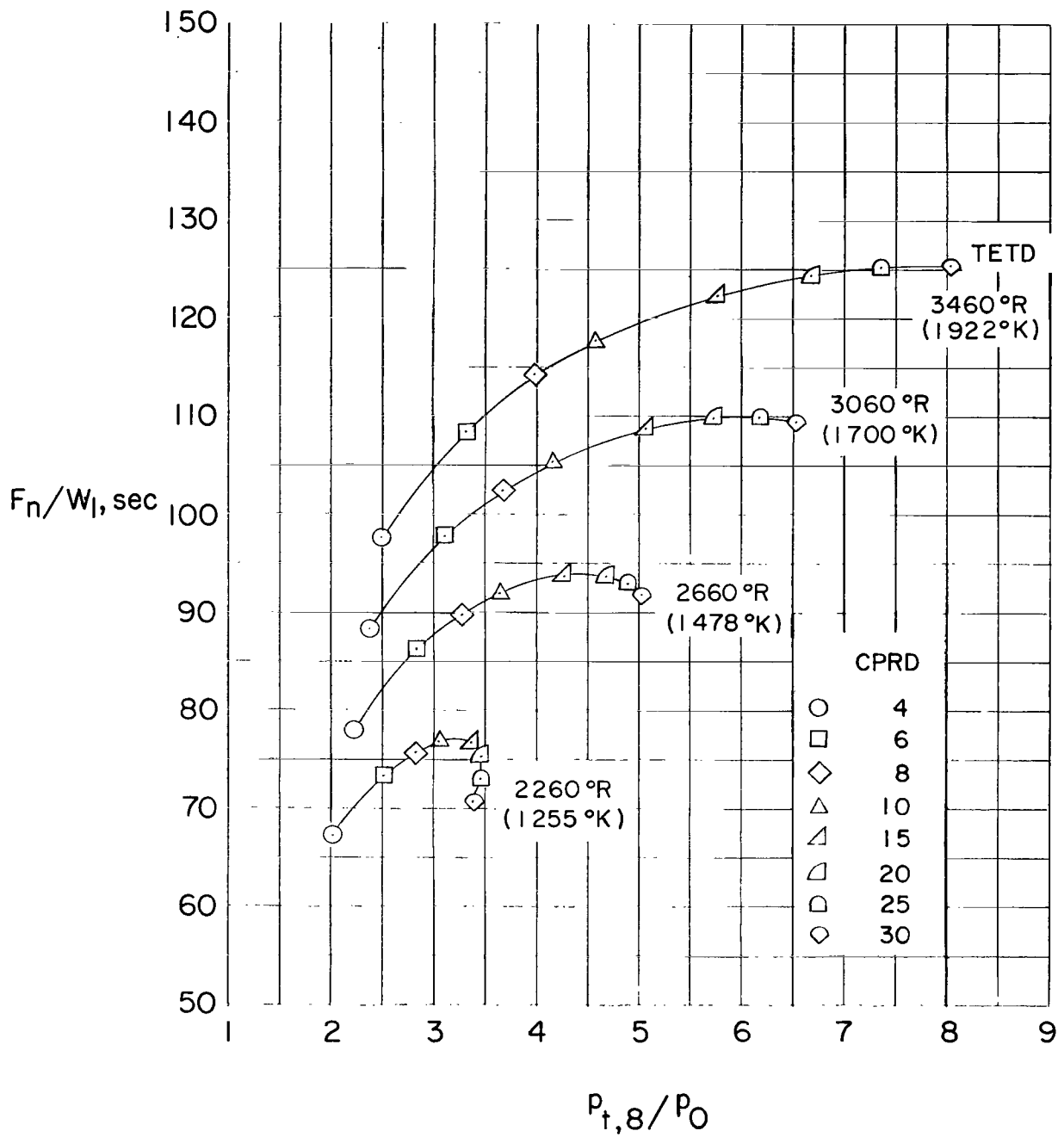


Figure 4.- Schedule of air-inlet total-pressure recovery used for all engine designs.



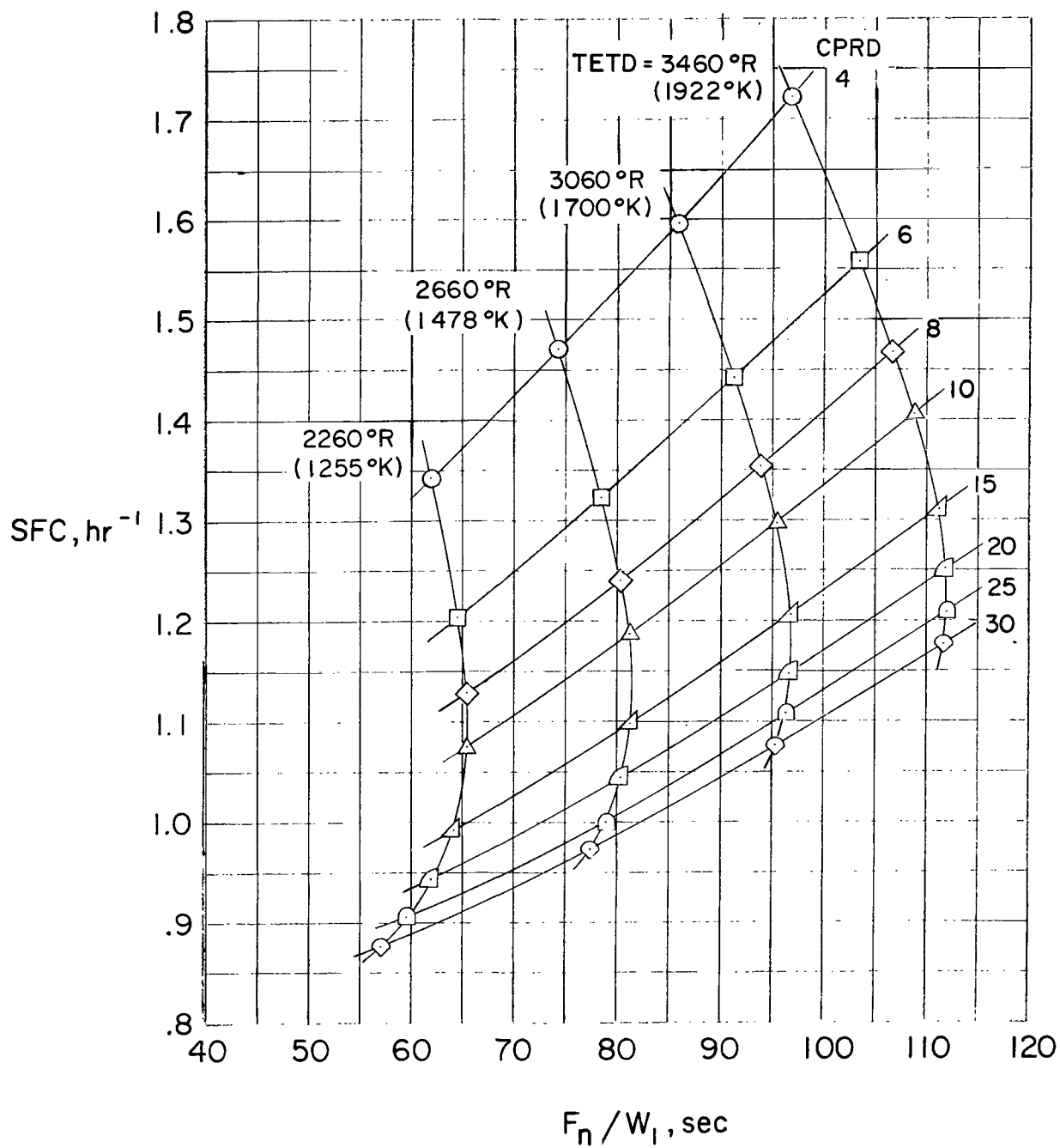
(a) SFC as a function of F_n/W_1 .

Figure 5.- Specific performance map of all design engines at sea-level static condition and maximum power.



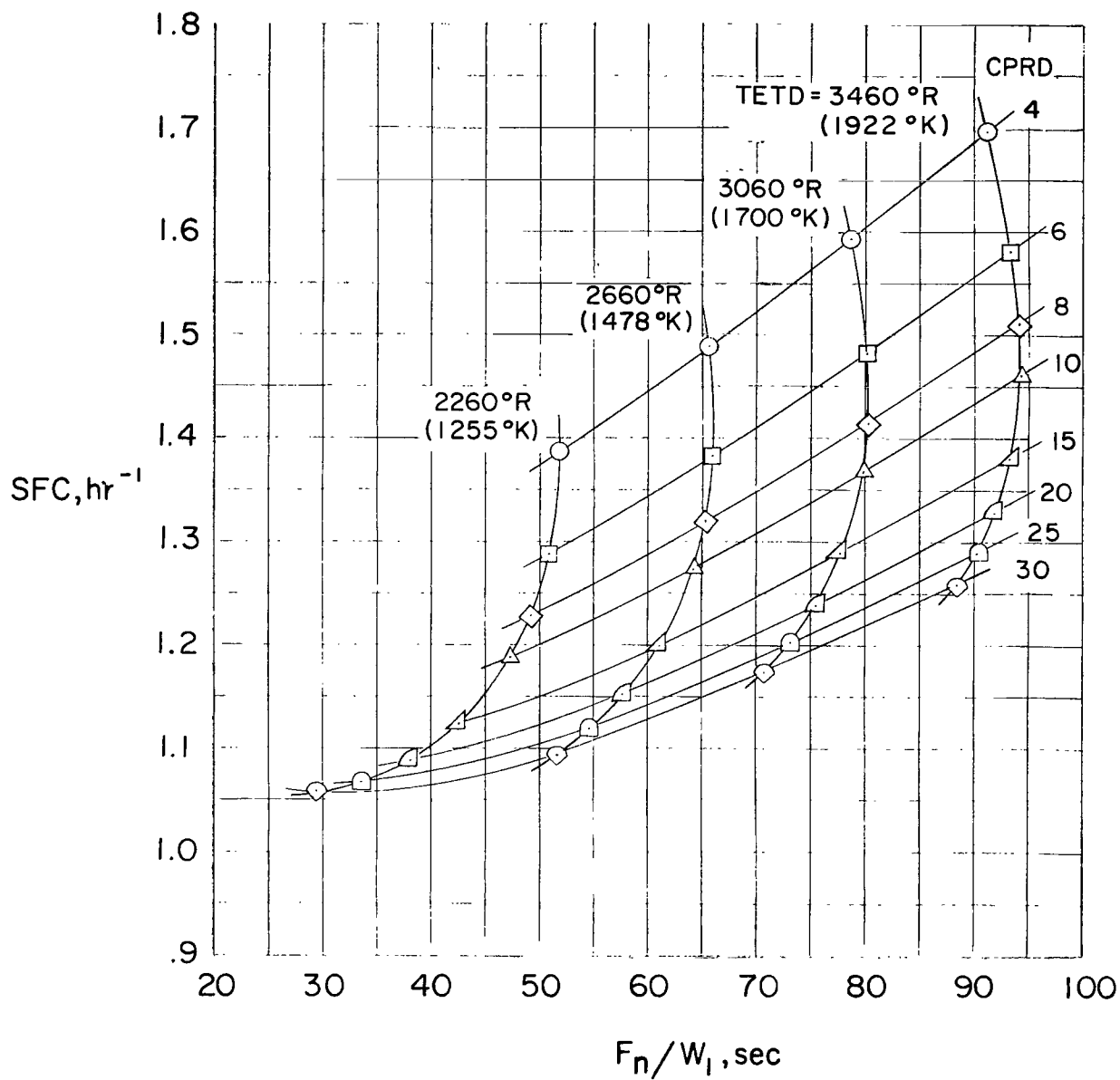
(b) F_n/W_1 as a function of nozzle-pressure ratio.

Figure 5.- Concluded.



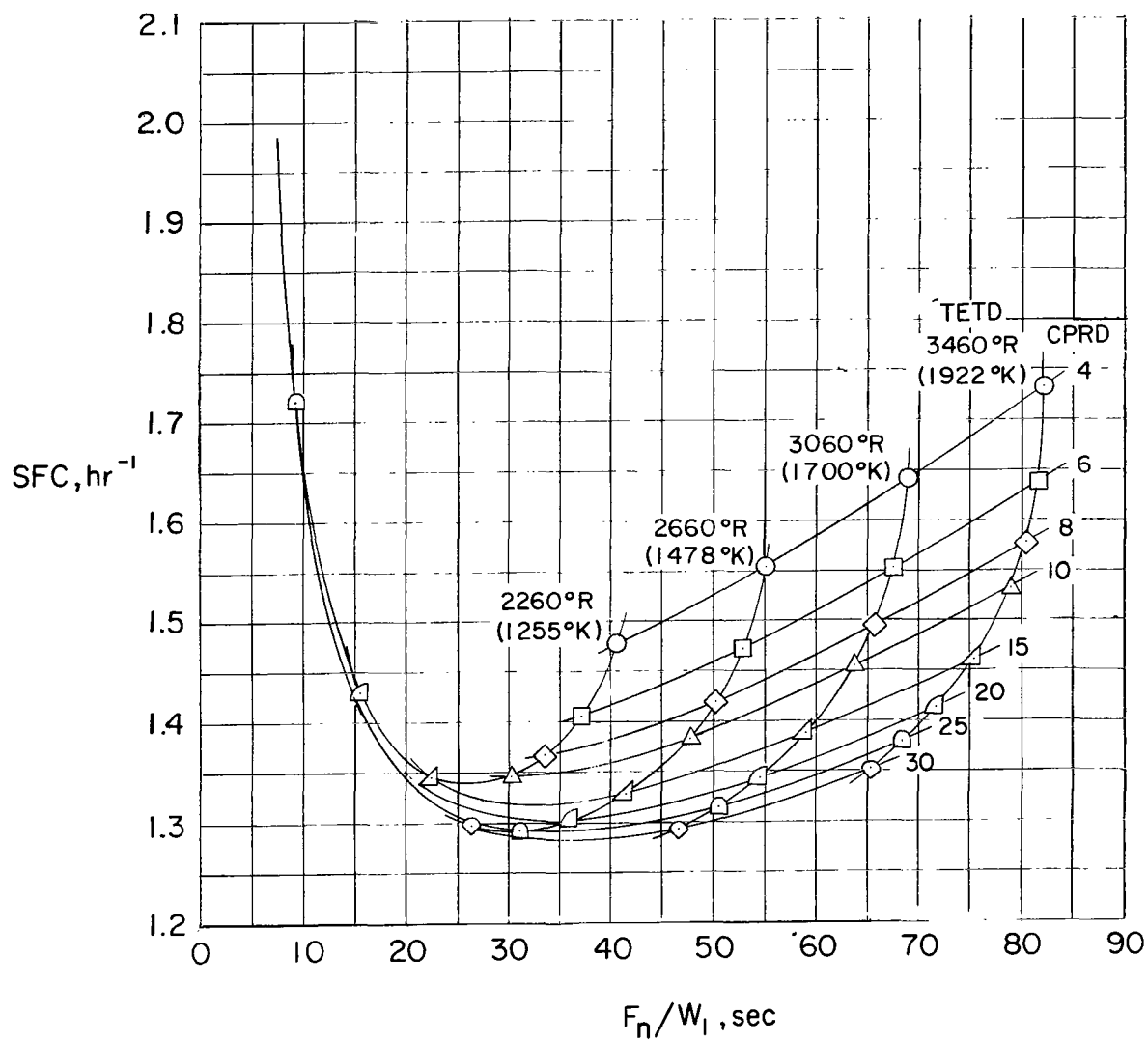
(a) $M = 1$; altitude, stratosphere.

Figure 6.- Specific performance map at maximum power.



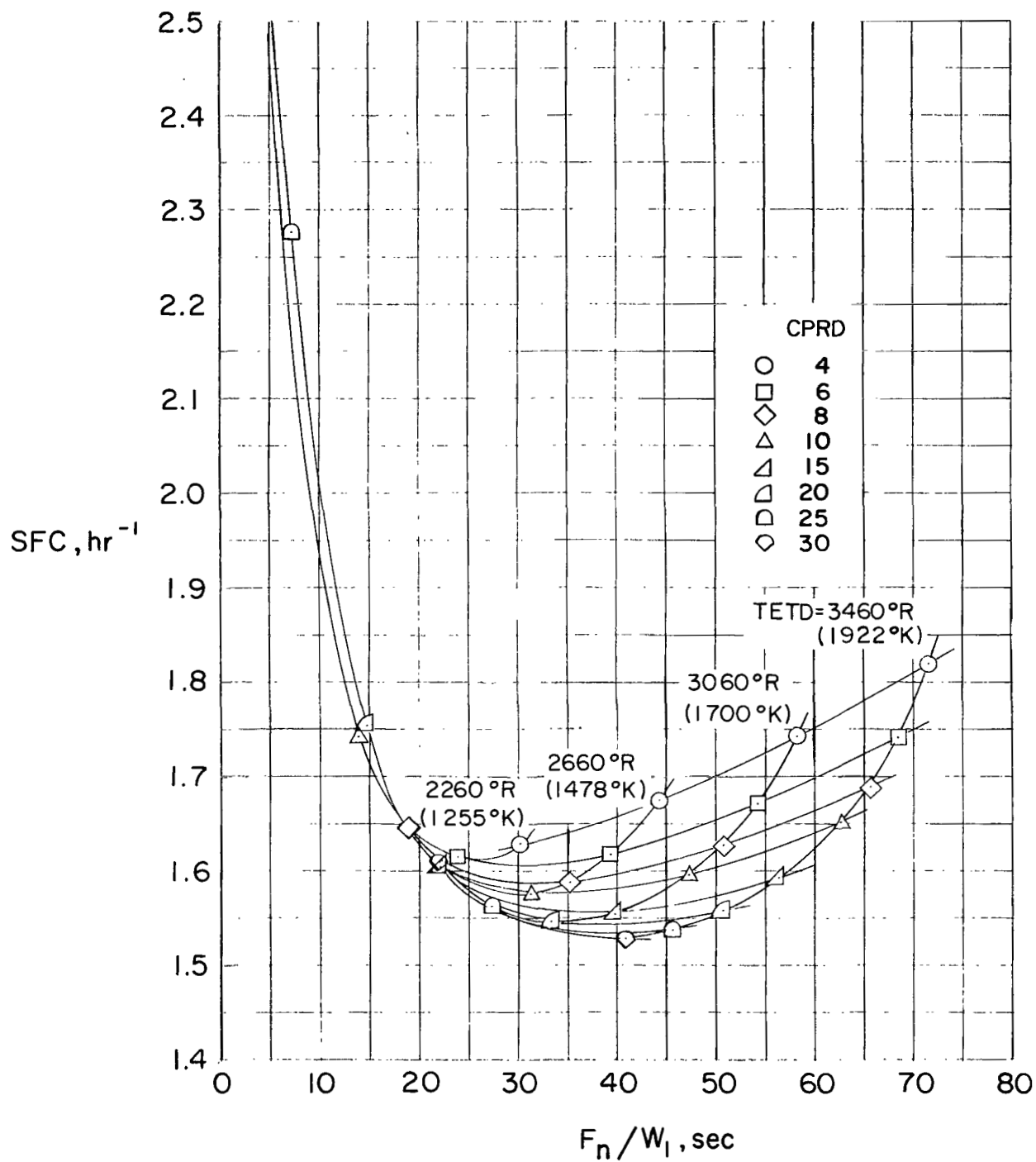
(b) $M = 2.0$; altitude, stratosphere.

Figure 6.- Continued.



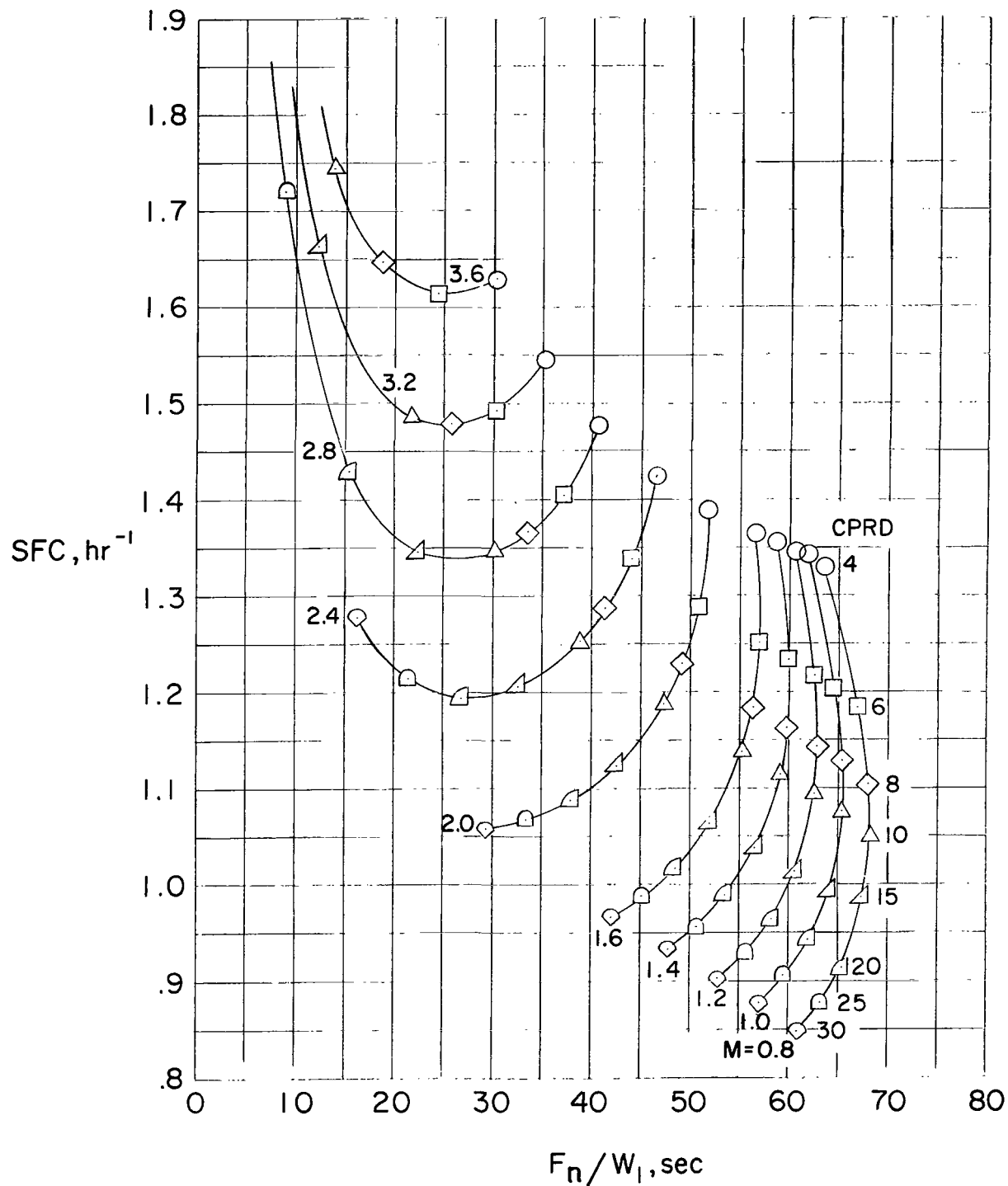
(c) $M = 2.8$; altitude, stratosphere.

Figure 6.- Continued.



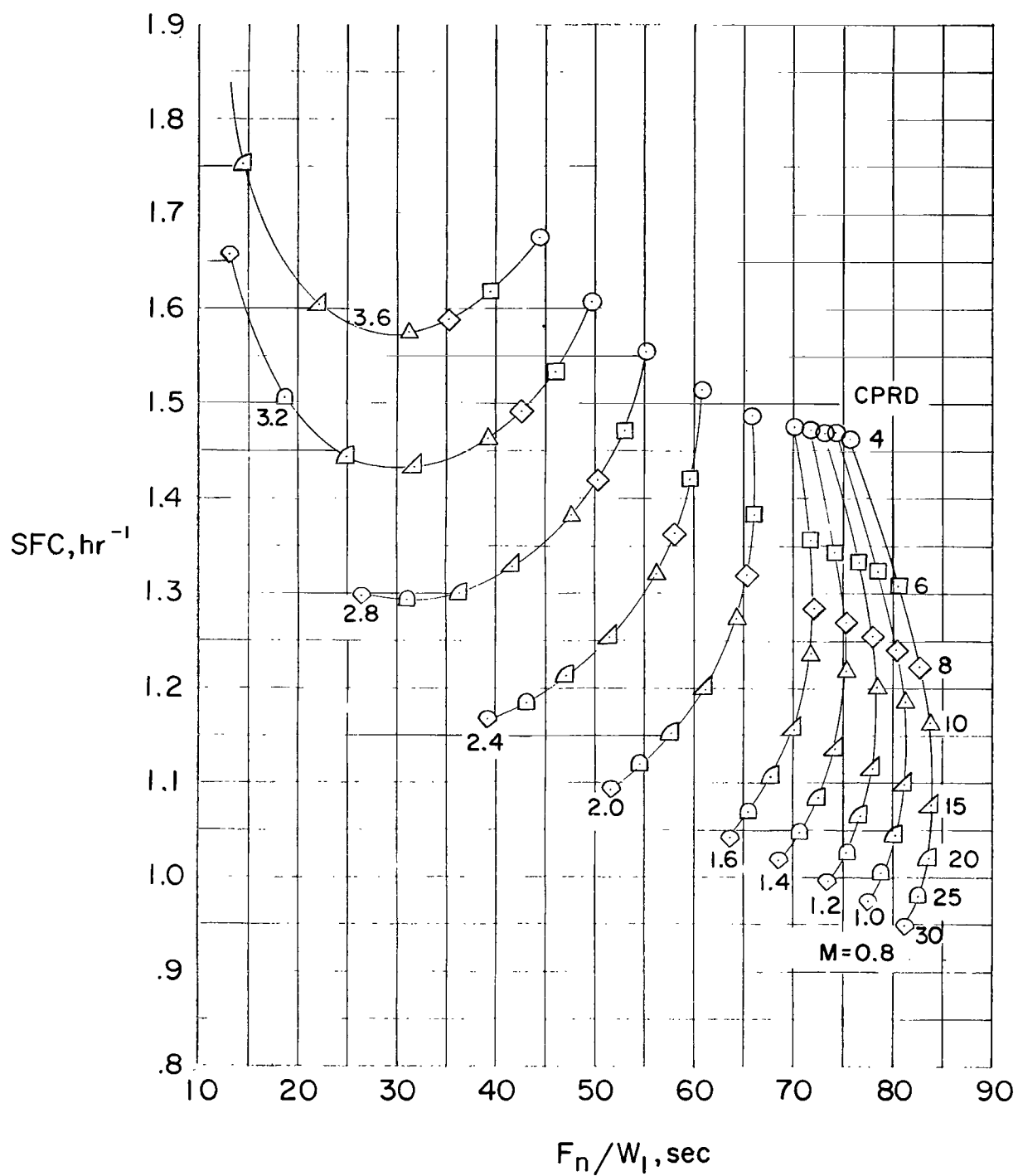
(d) $M = 3.6$; altitude, stratosphere.

Figure 6.- Concluded.



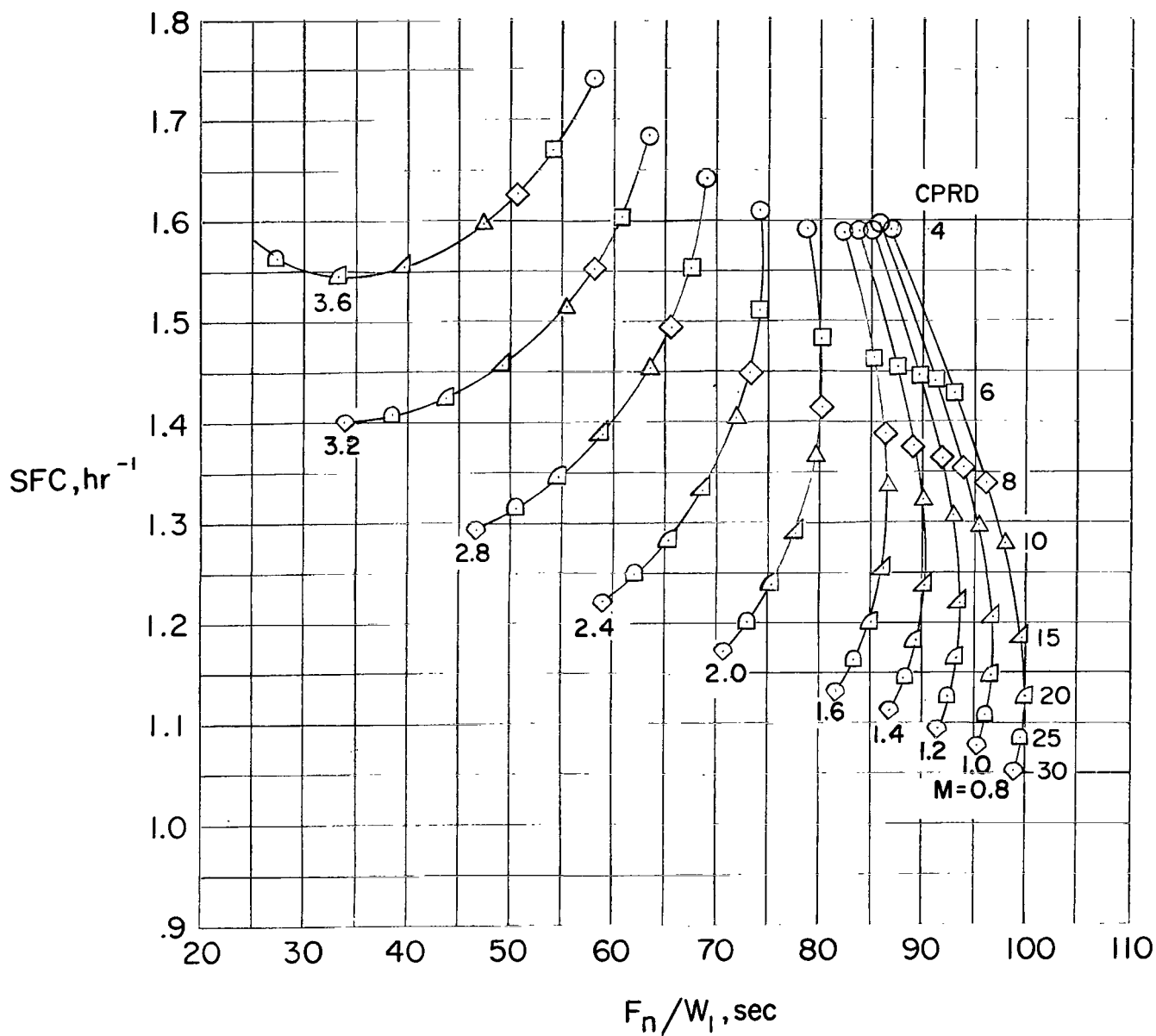
(a) TETD = 2260°R (1255°K).

Figure 7.- Effect of Mach number on specific performance of design-point engines at maximum power. Altitude, stratosphere.



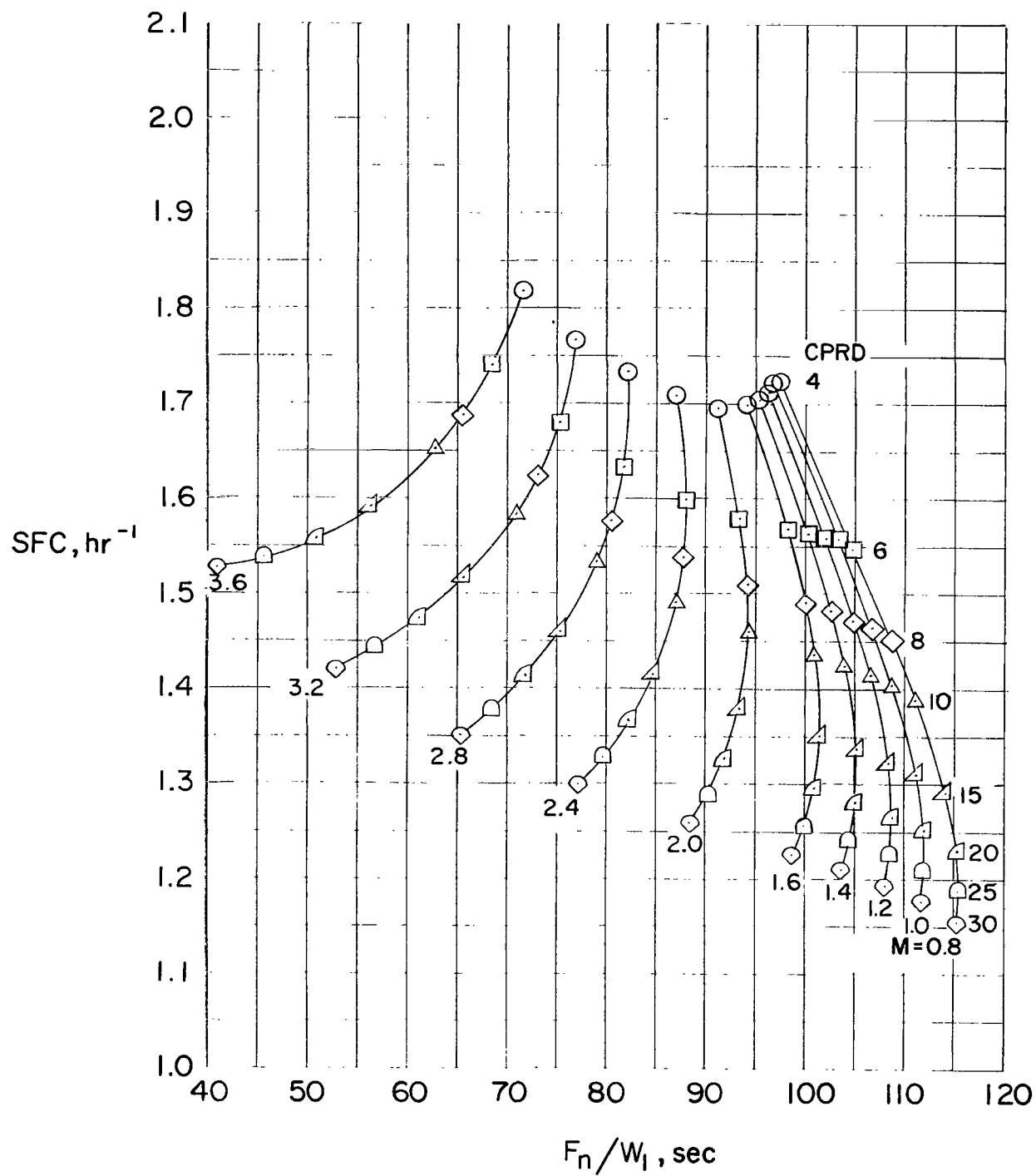
(b) TETD = 2660° R (1478°K).

Figure 7.- Continued.



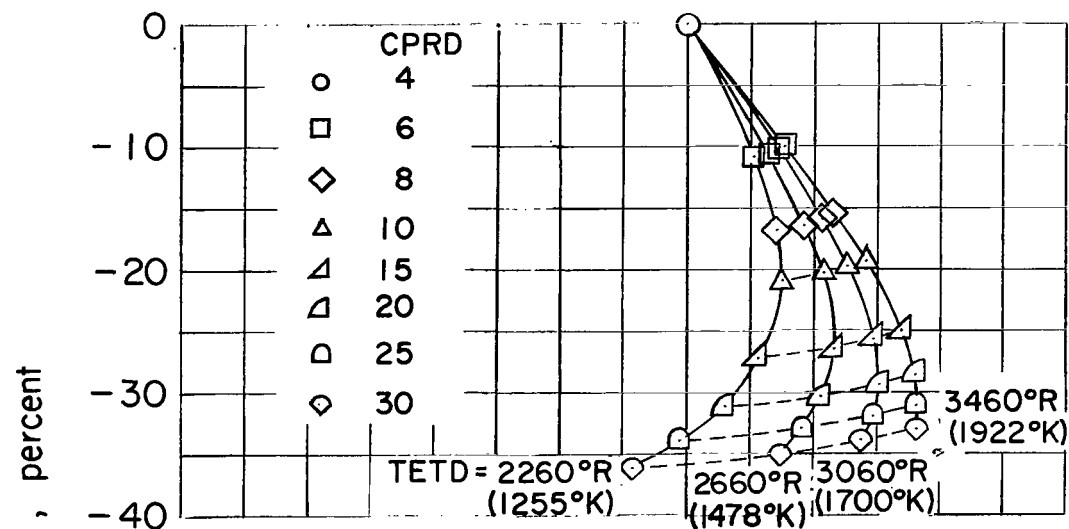
(c) TETD = 3060° R (1700° K).

Figure 7.- Continued.

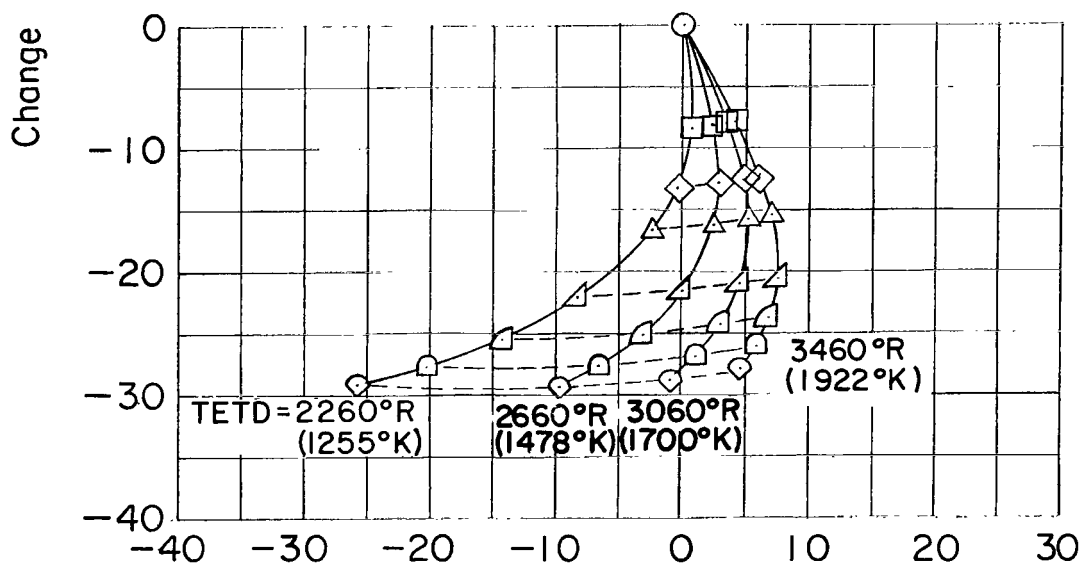


(d) TETD = 3460° R (1922° K).

Figure 7.- Concluded.

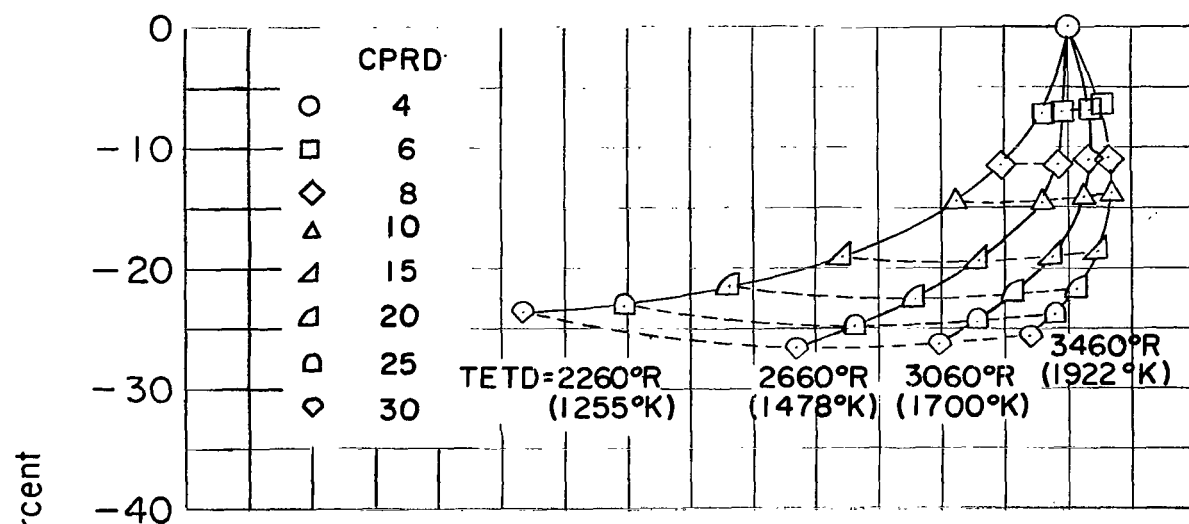


(a) $M = 0.8$.

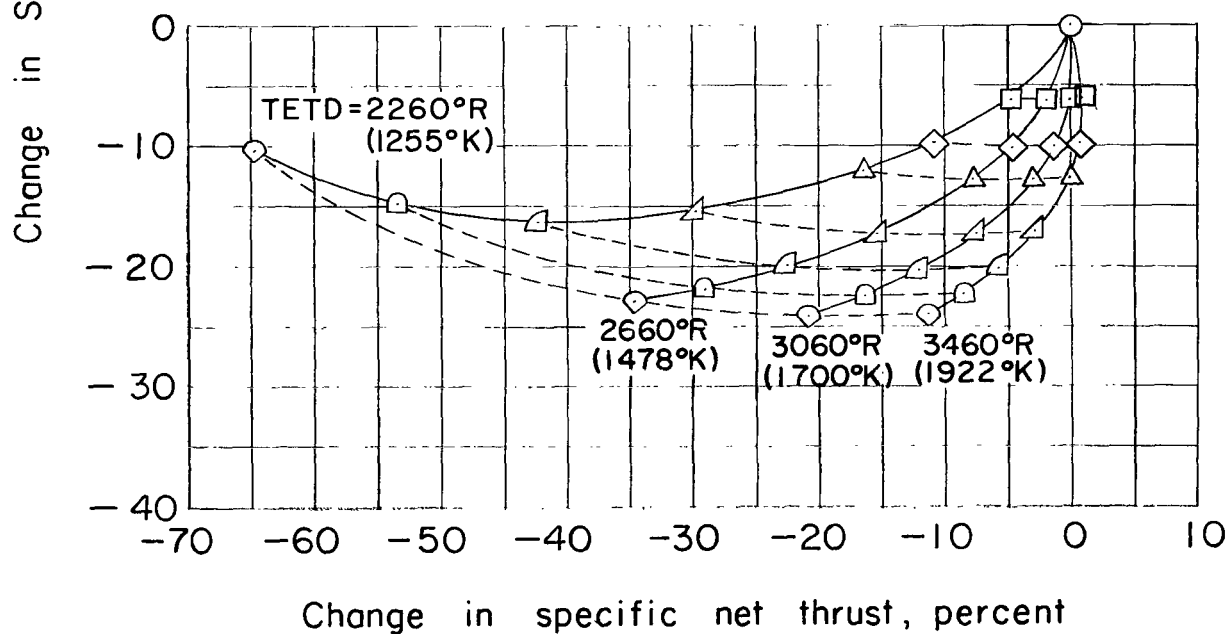


(b) $M = 1.6$.

Figure 8.- Relative change in specific performance due to increase in CPRD from 4 to 30. Altitude, stratosphere.

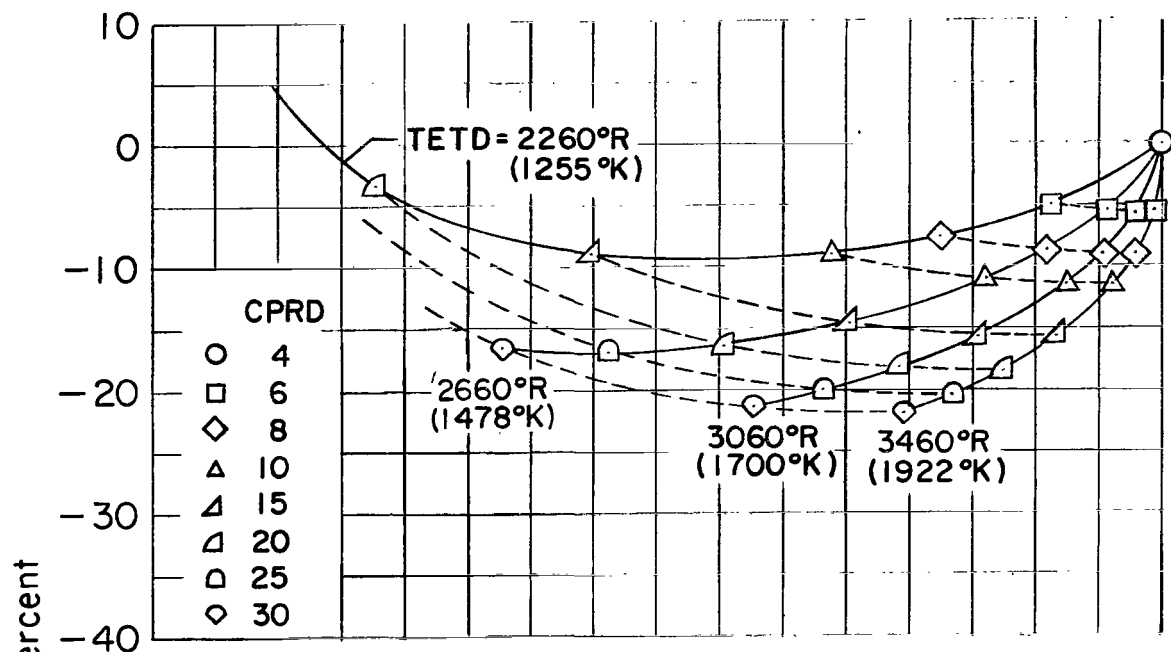


(c) $M = 2.0$.

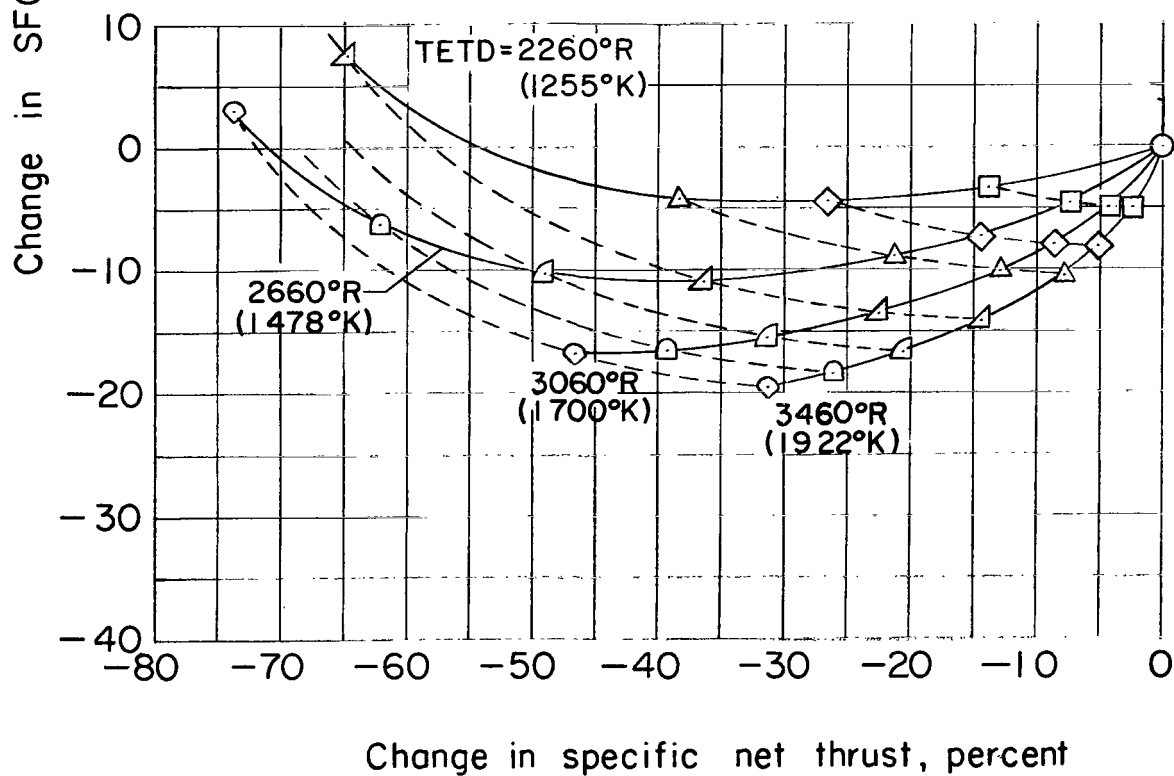


(d) $M = 2.4$.

Figure 8.- Continued.

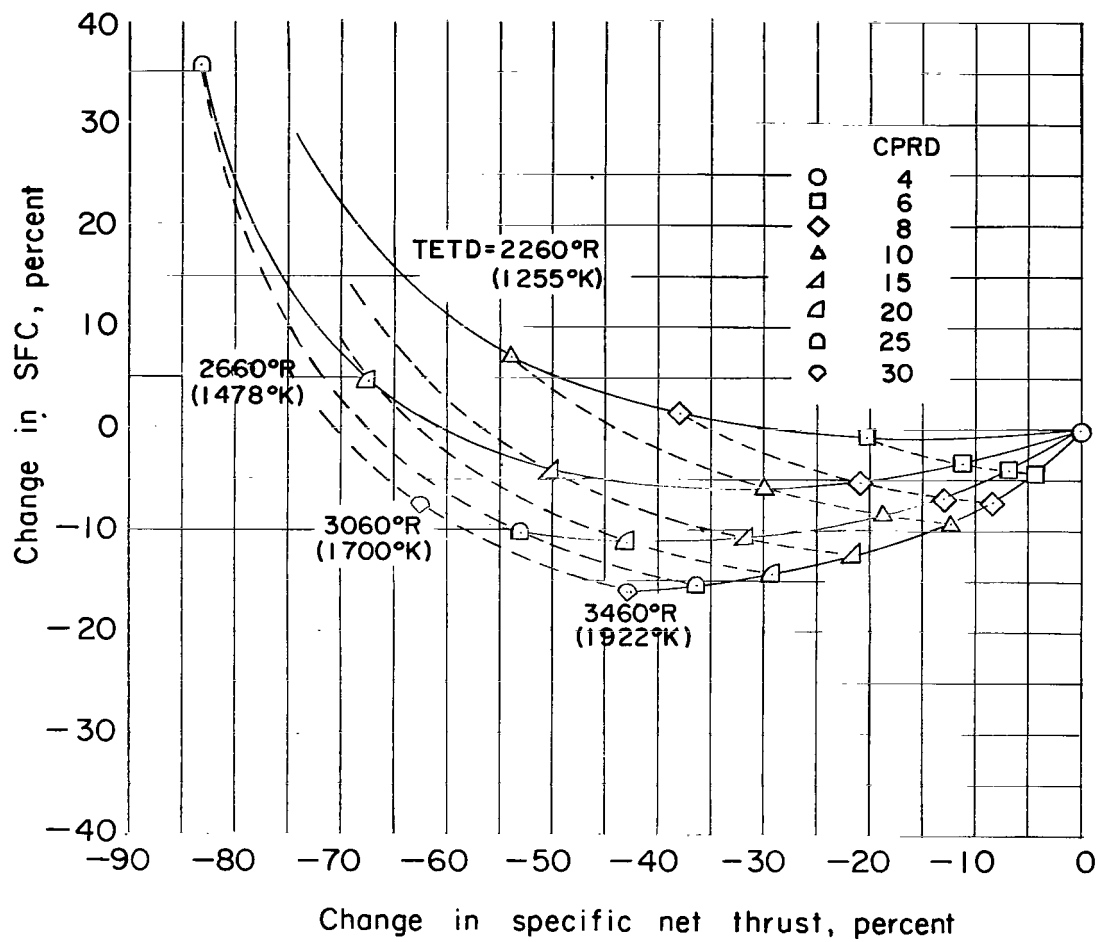


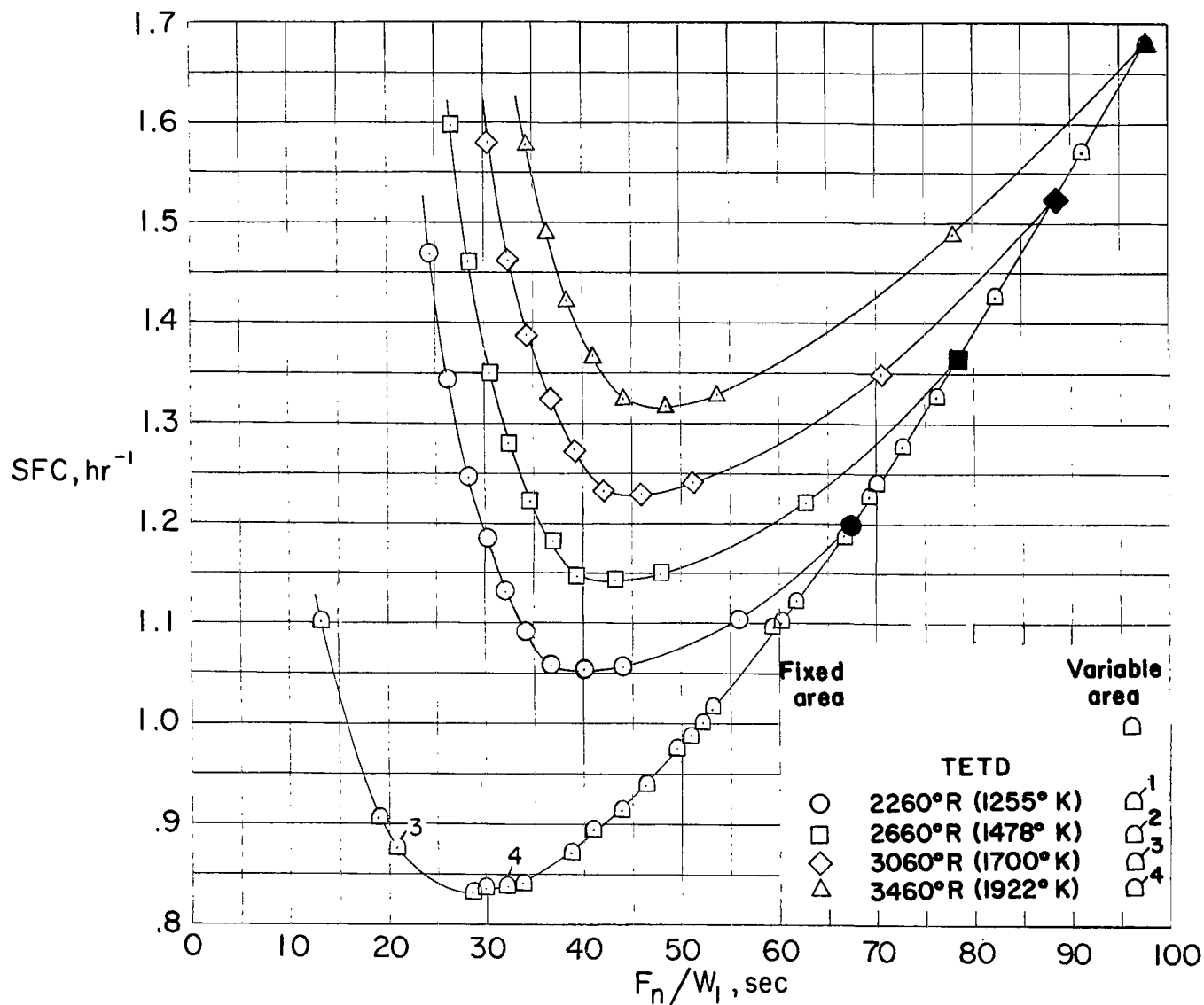
(e) $M = 2.8$.



(f) $M = 3.2$.

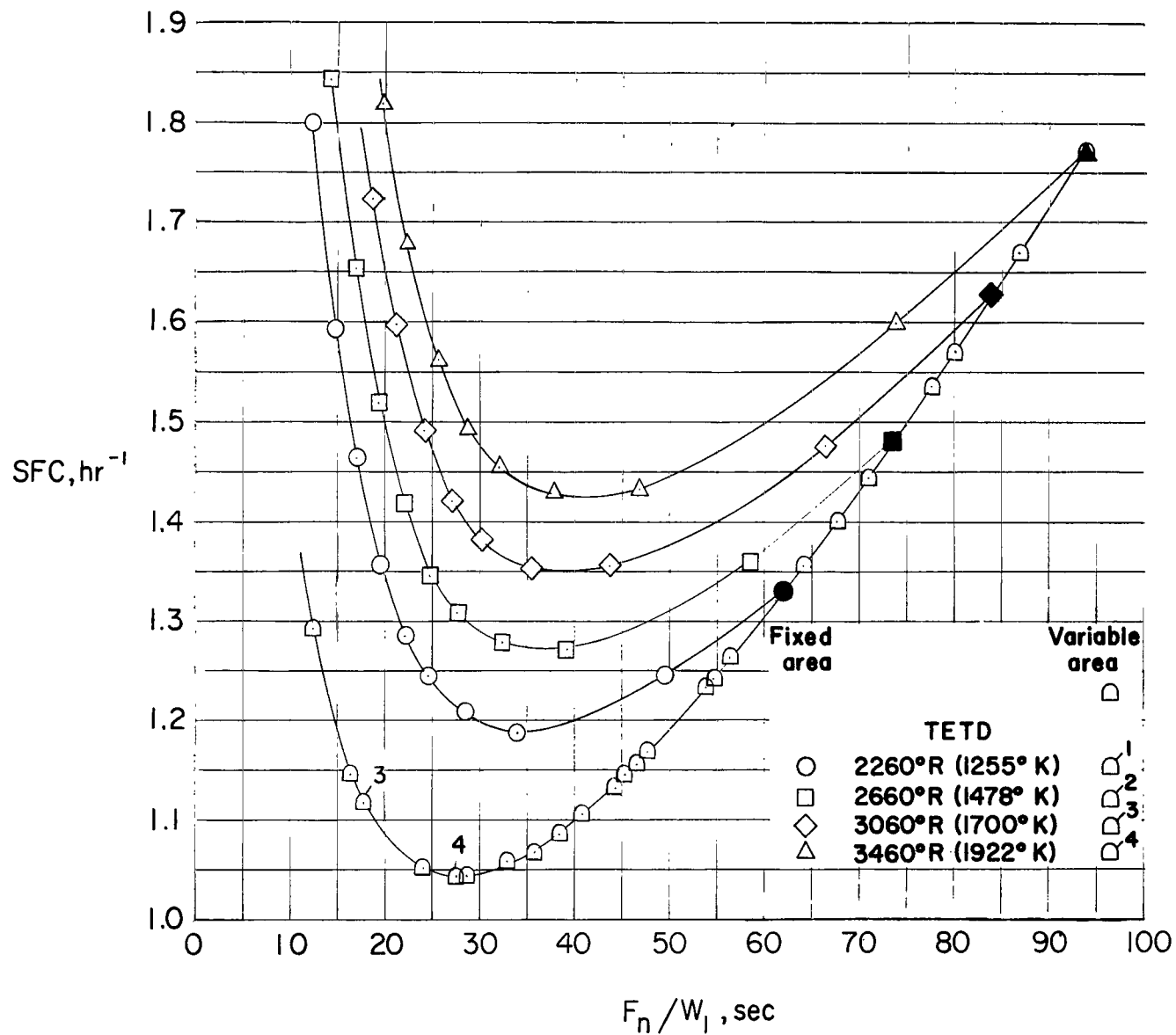
Figure 8.- Continued.





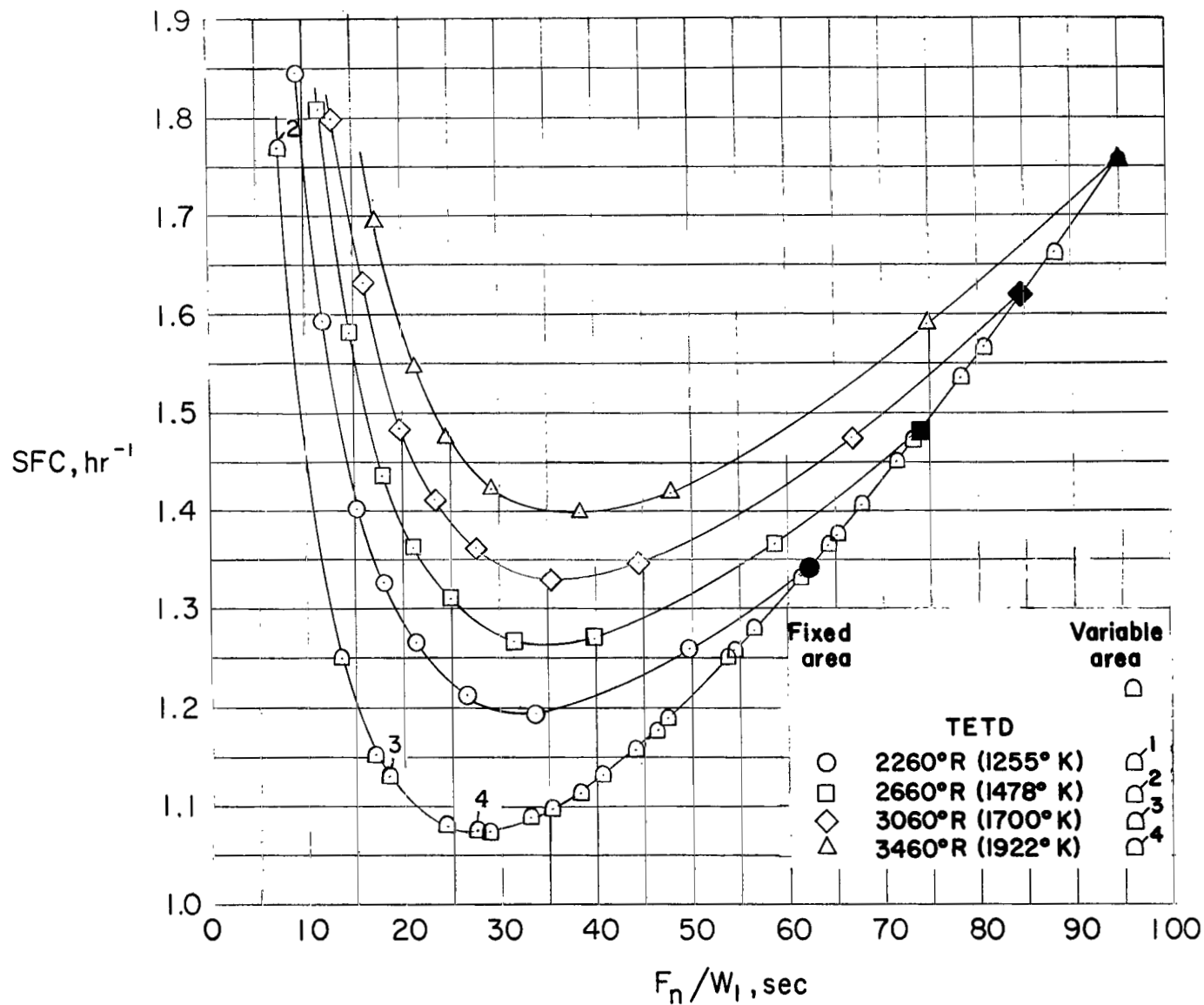
(a) $M = 0$; Altitude = 0.

Figure 9.- Specific performance of engines with CPRD of 4 at partial-power operation. (Solid symbols indicate maximum power. Numbers on symbols indicate 40-percent reduction in turbine area for designated TETD.)



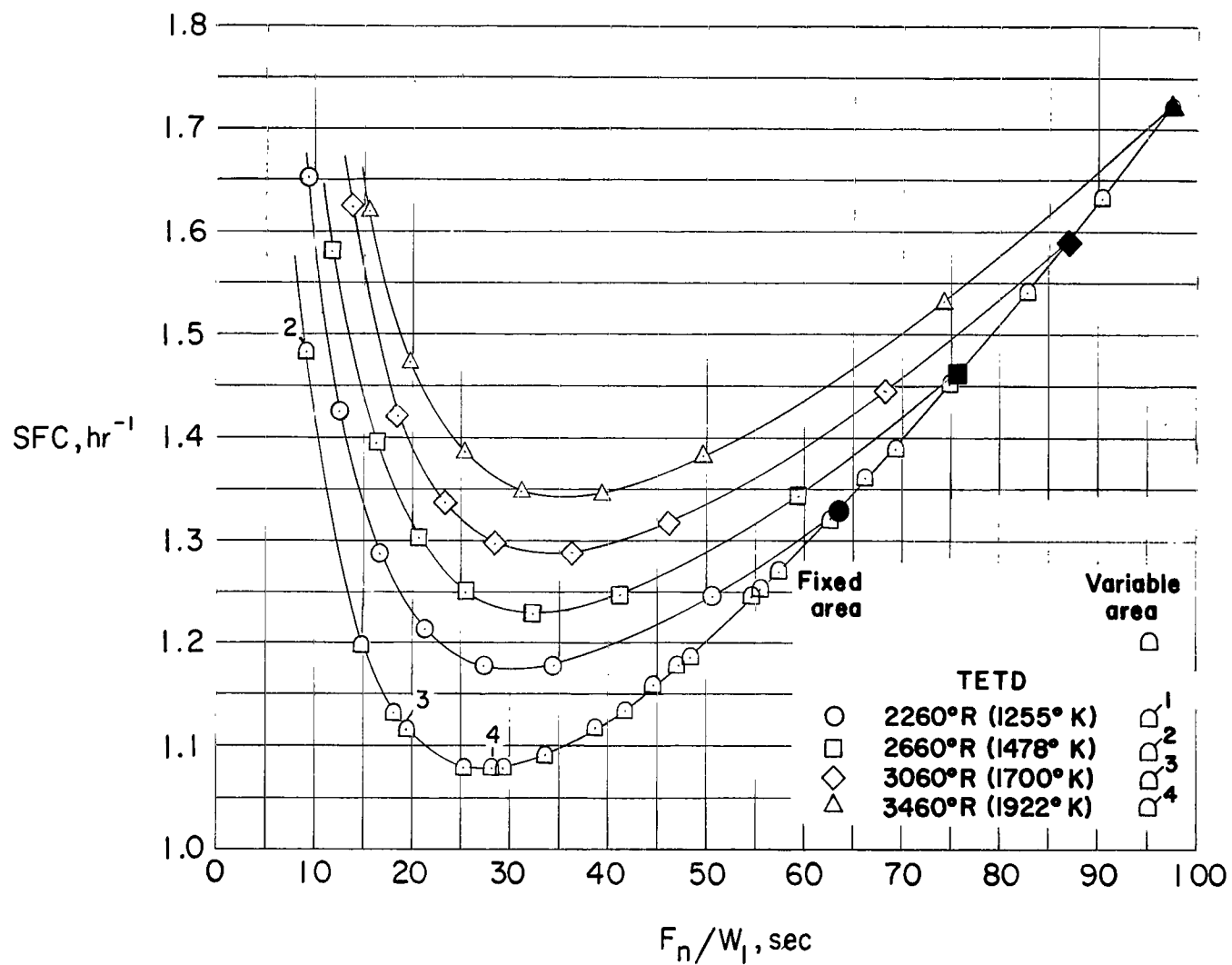
(b) $M = 0.4$; Altitude = 15000 ft (4572 m).

Figure 9.- Continued.



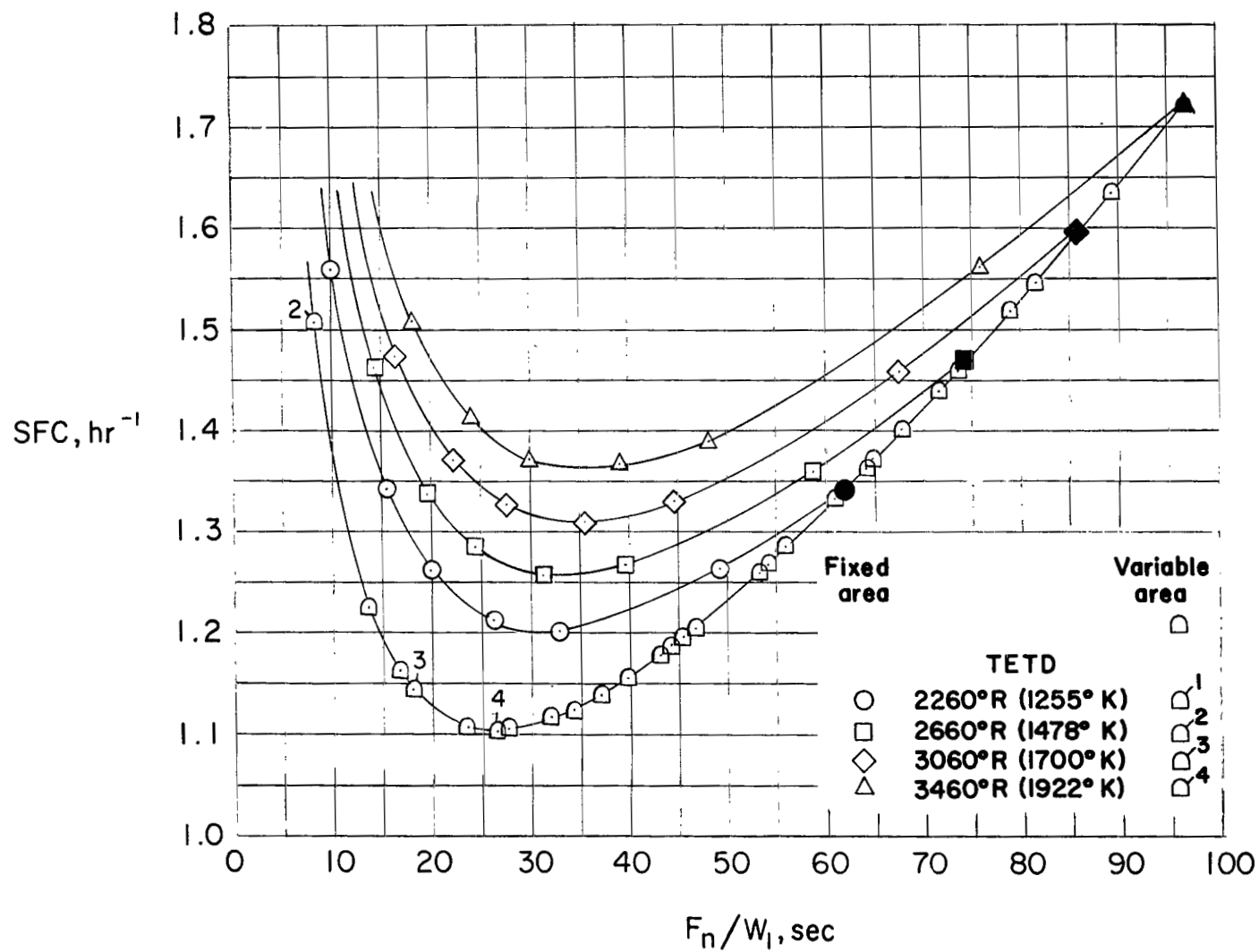
(c) $M = 0.6$; Altitude = 25 000 ft (7620 m).

Figure 9.- Continued.



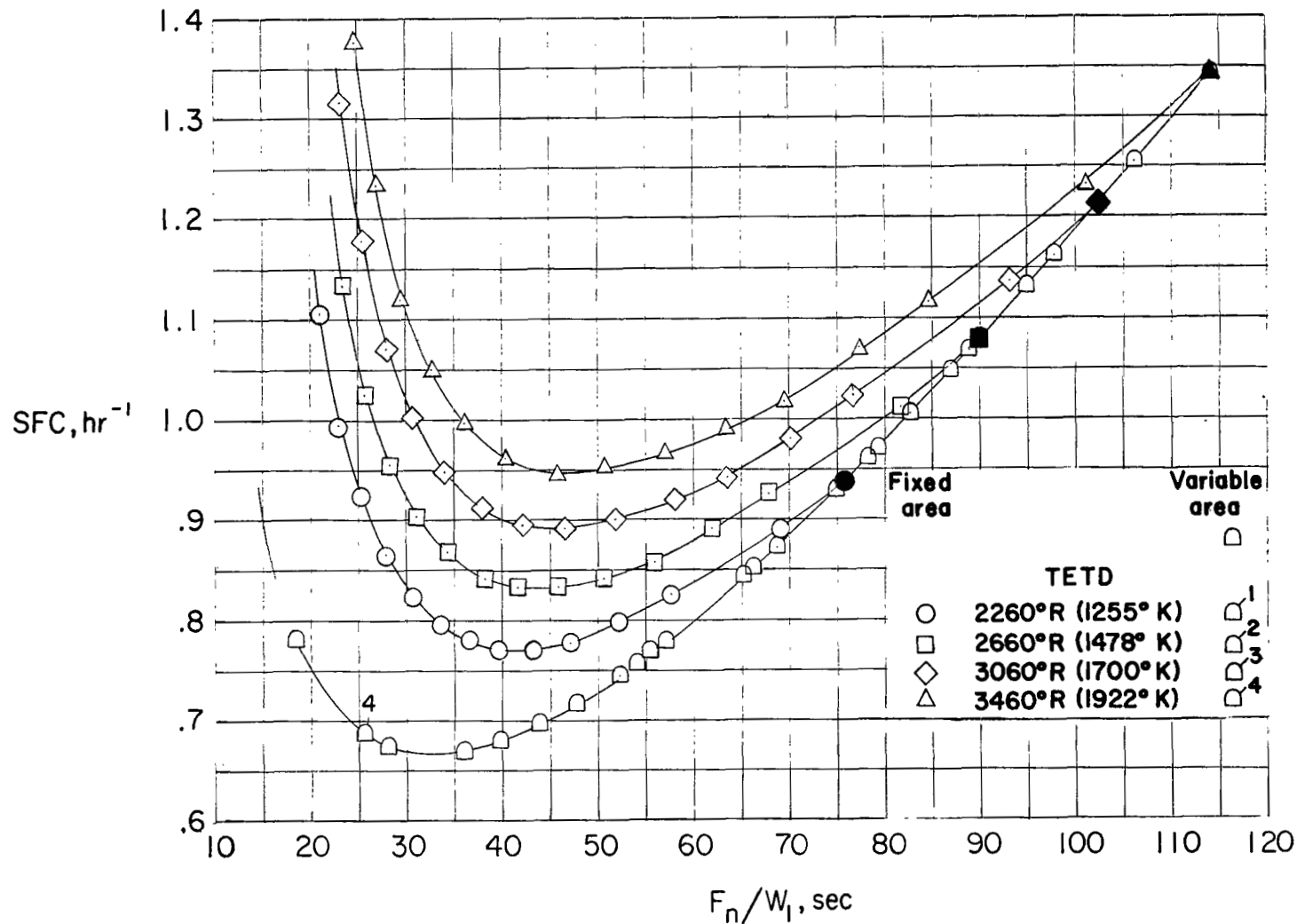
(d) $M = 0.8$; altitude, stratosphere.

Figure 9.- Continued.



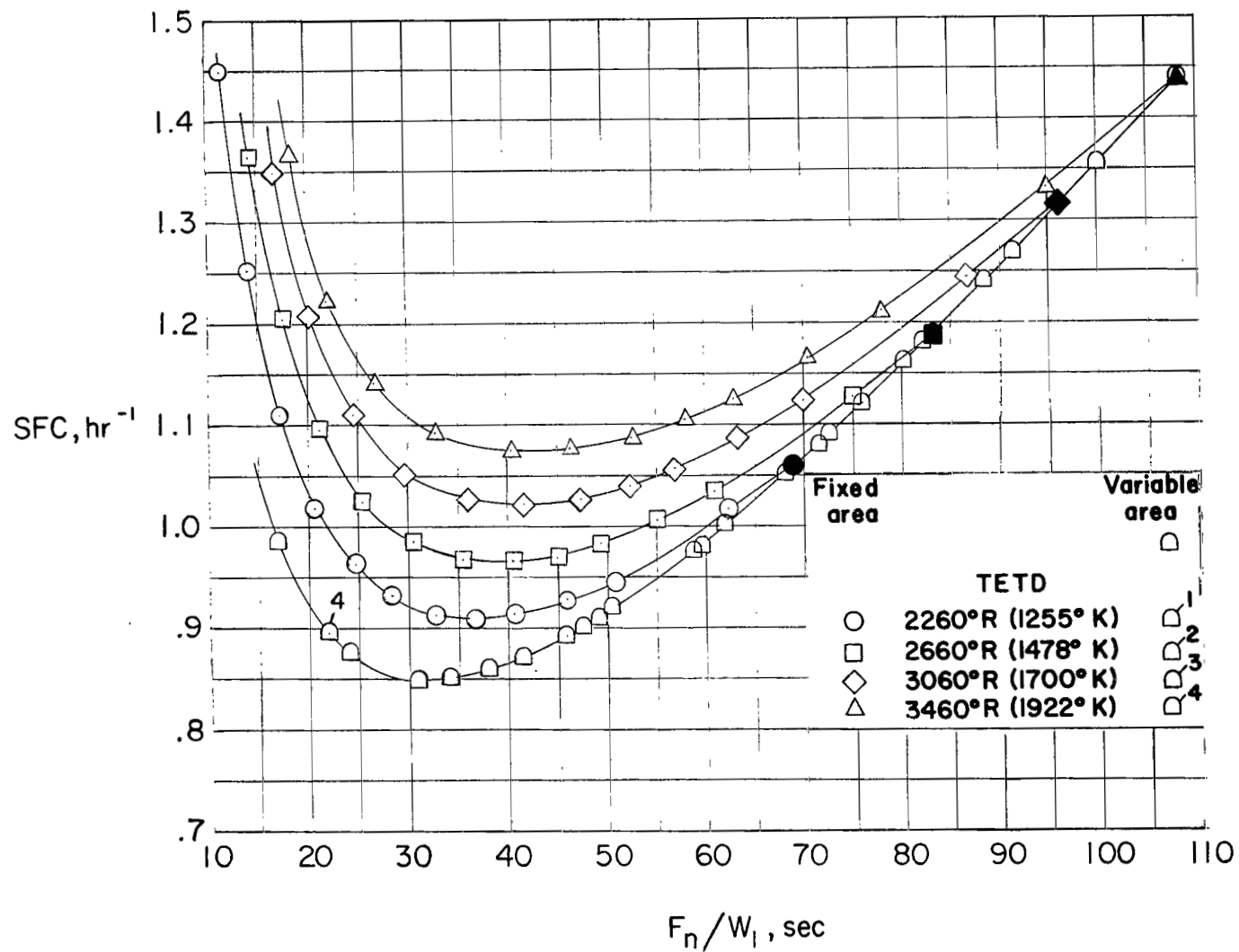
(e) $M = 1.0$; altitude, stratosphere.

Figure 9.- Concluded.



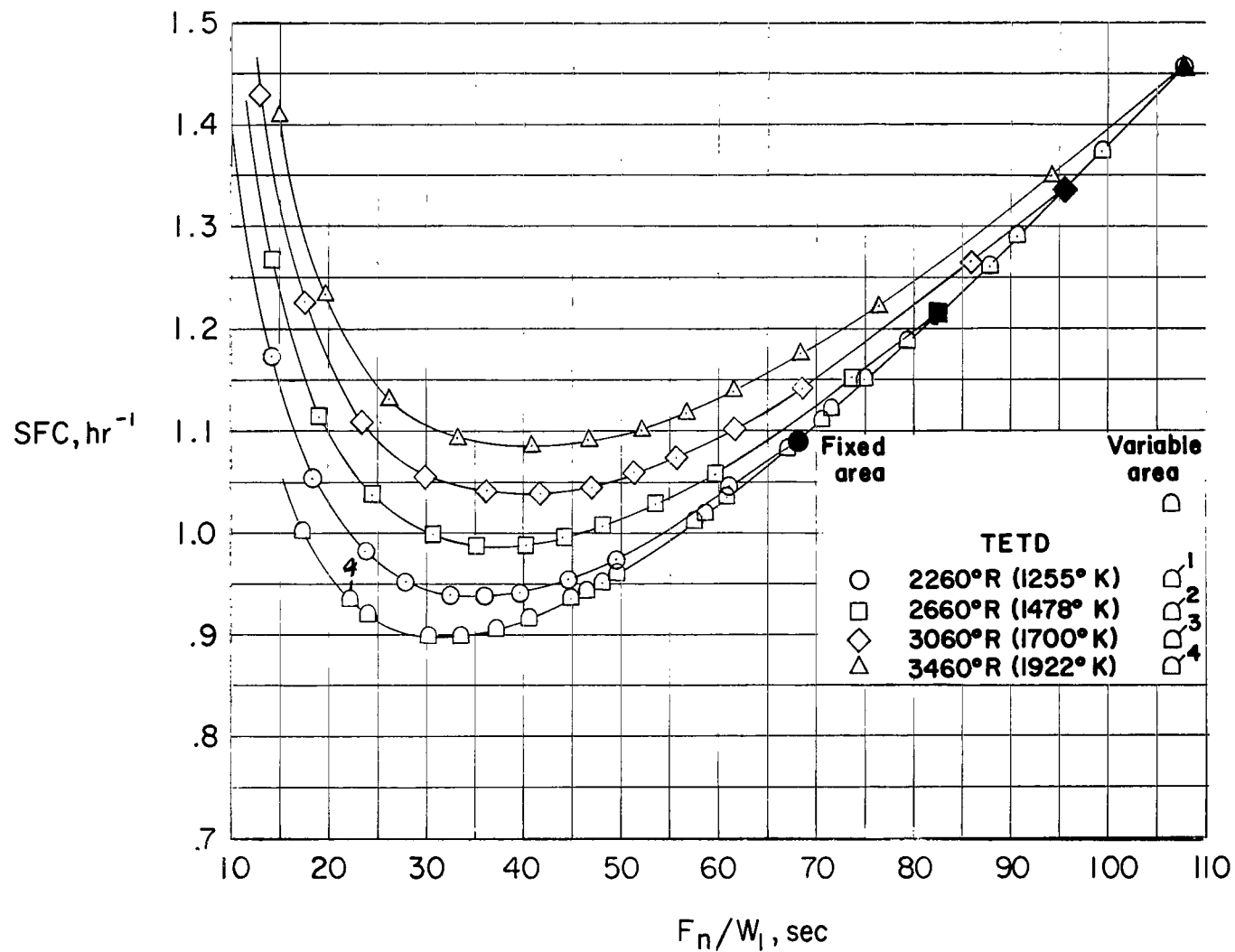
(a) $M = 0$; Altitude = 0.

Figure 10.- Specific performance of engines with CPRD of 8 at partial-power operation. (Solid symbols indicate maximum power. Numbers on symbols indicate 40-percent reduction in turbine area for designated TETD.)



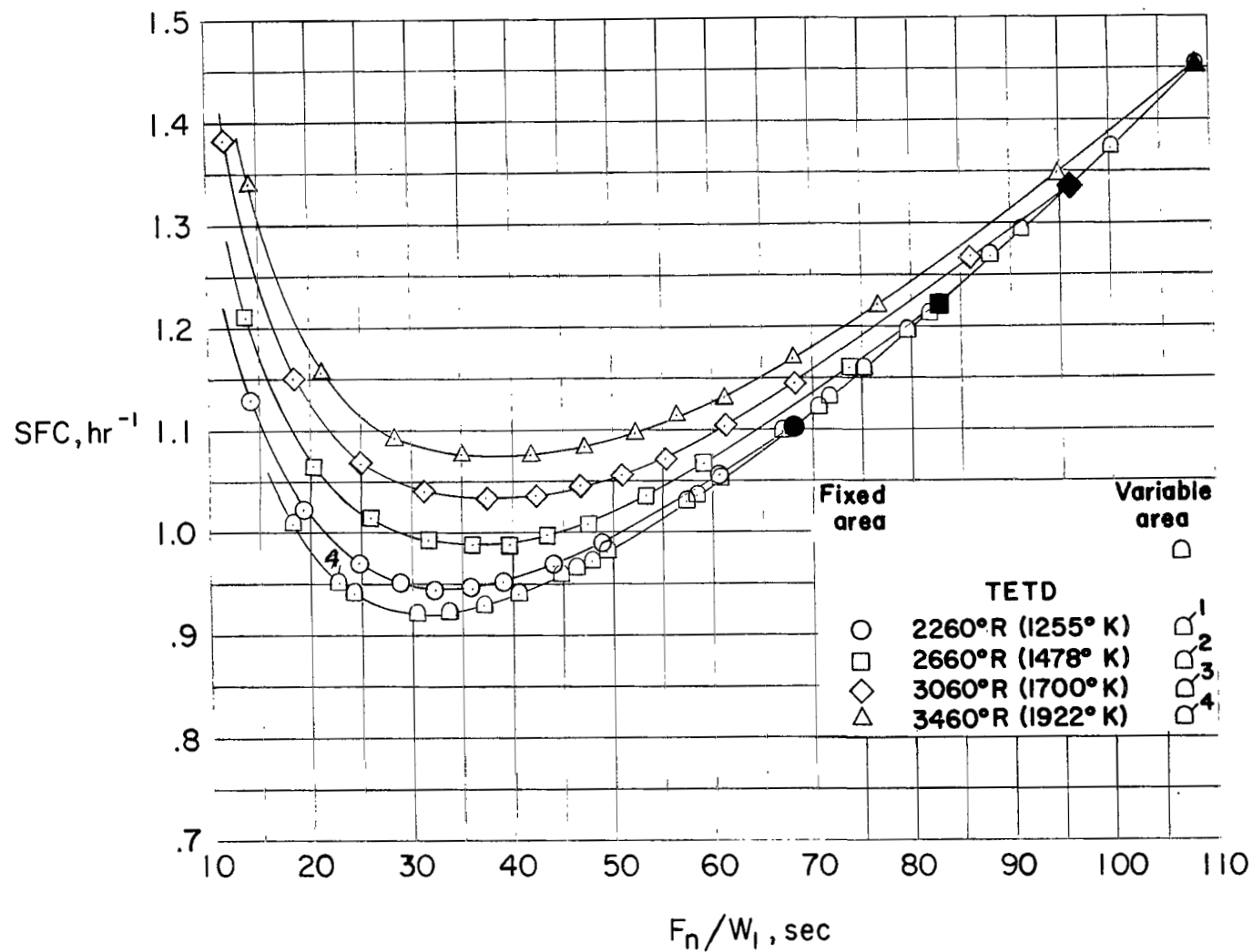
(b) $M = 0.4$; Altitude = 15 000 ft (4572 m).

Figure 10.- Continued.



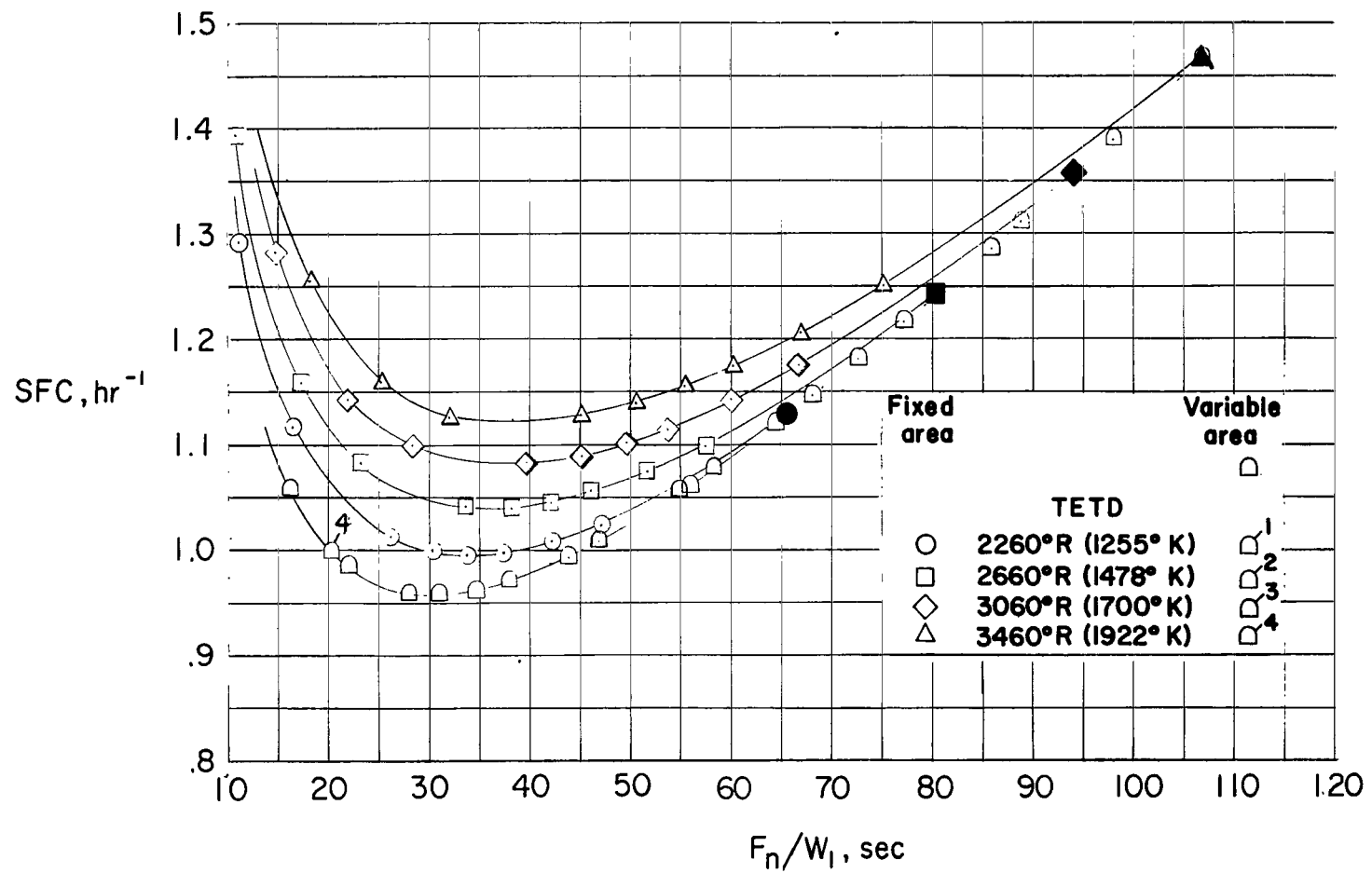
(c) $M = 0.6$; Altitude = 25 000 ft (7620 m).

Figure 10.- Continued.



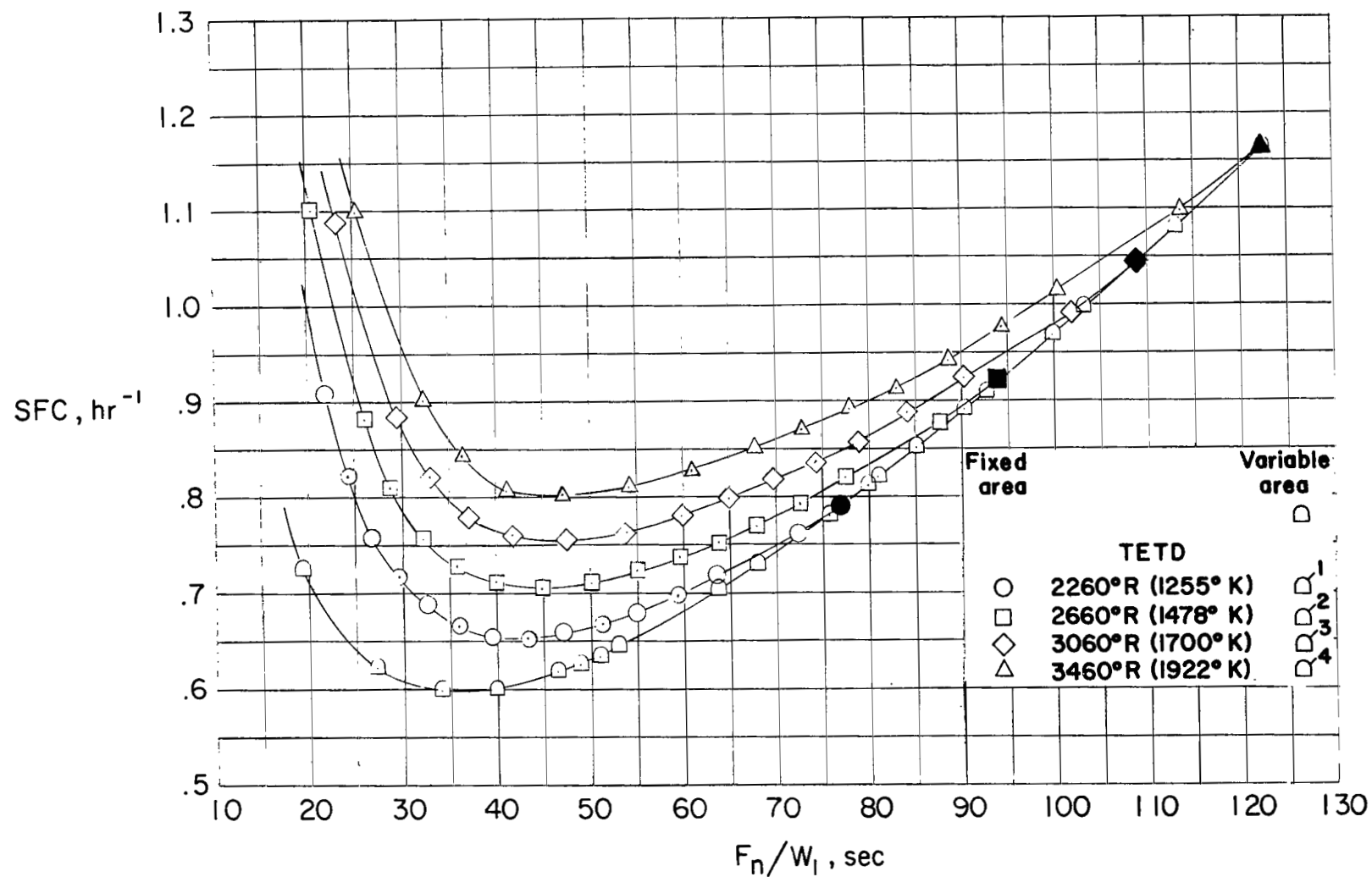
(d) $M = 0.8$; altitude, stratosphere.

Figure 10.- Continued.



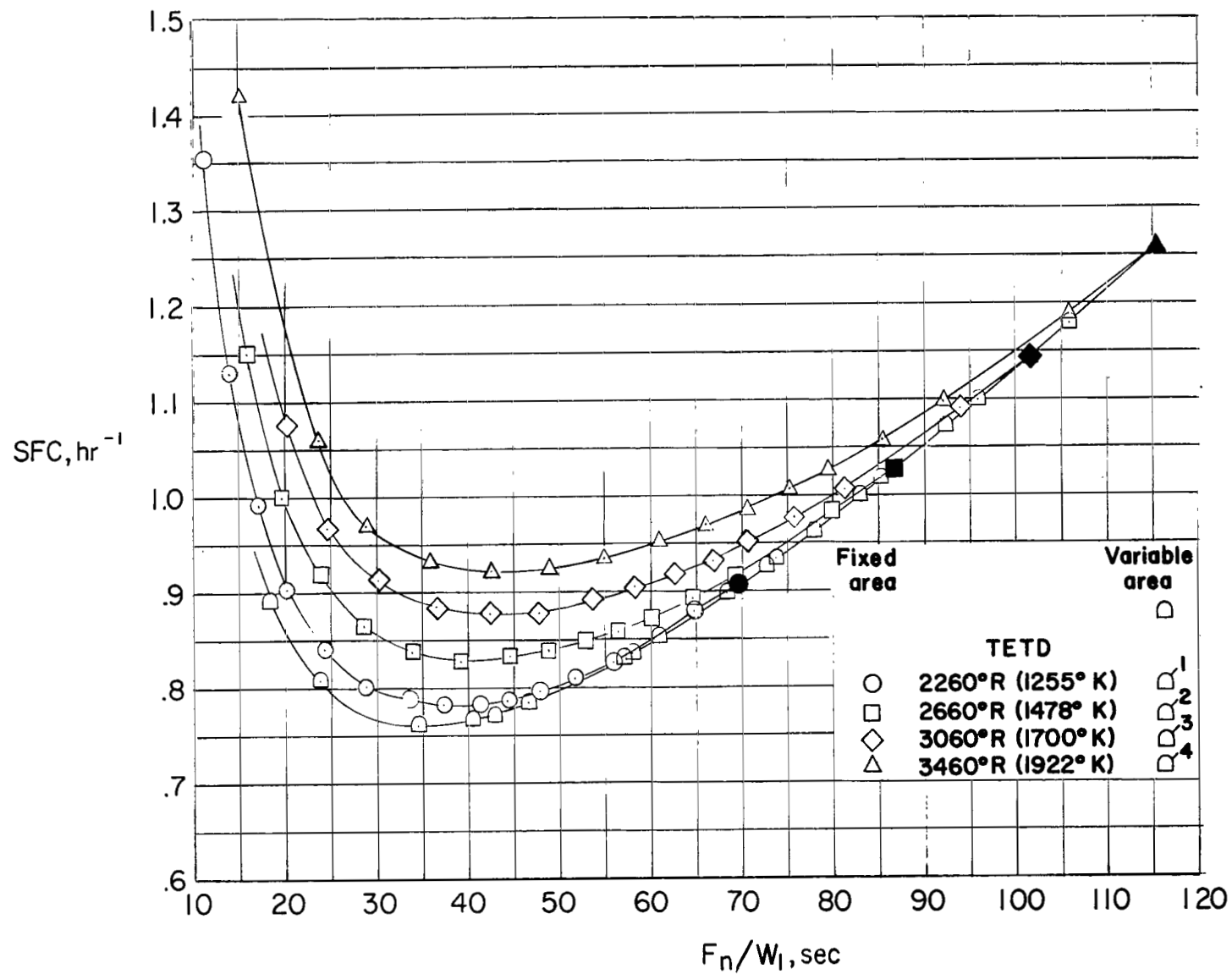
(e) $M = 1.0$; altitude, stratosphere.

Figure 10.- Concluded.



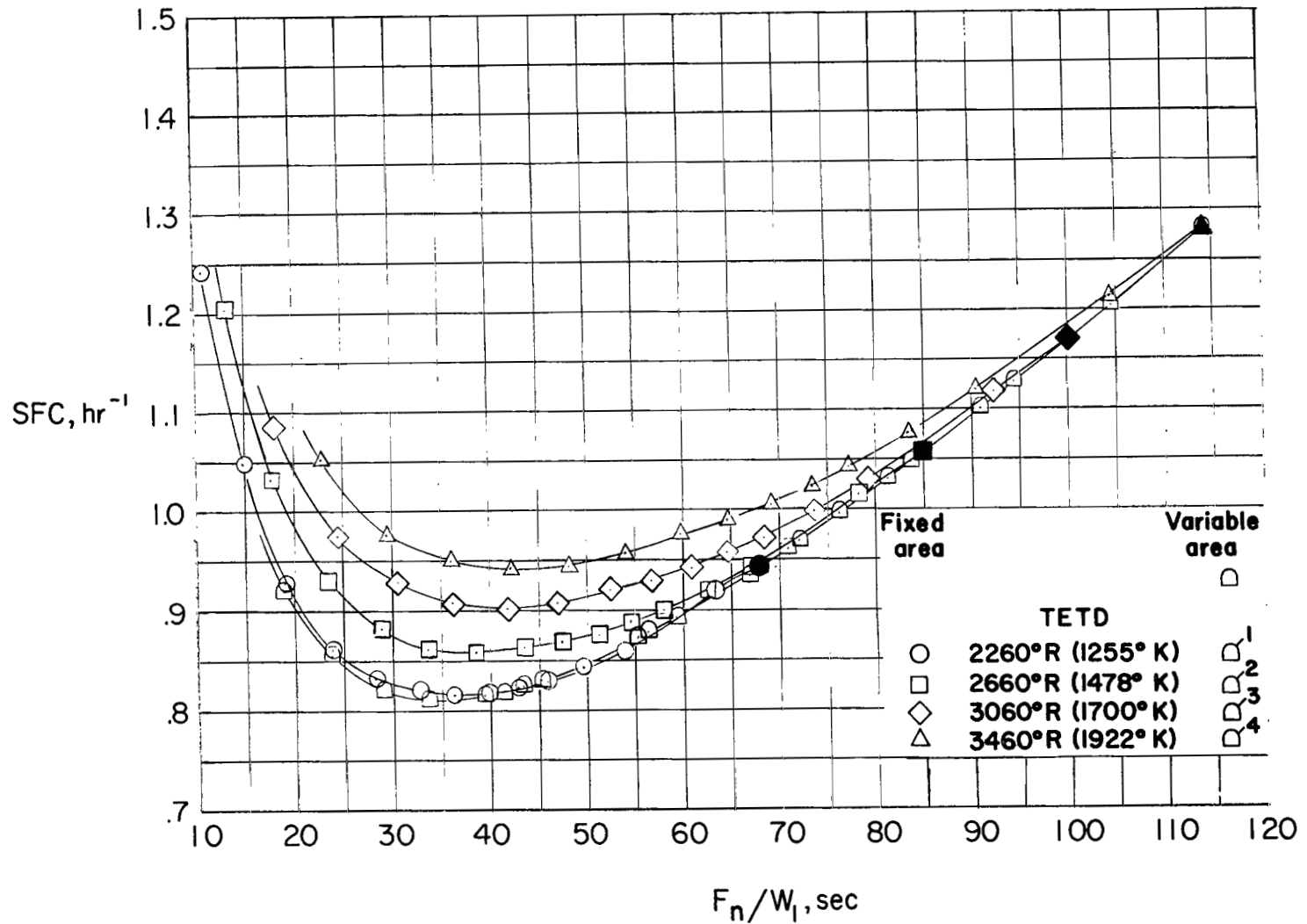
(a) $M = 0$; Altitude = 0.

Figure 11.- Specific performance of engines with CPRD of 15 at partial-power operation. (Solid symbols indicate maximum power. Numbers on symbols indicate 40-percent reduction in turbine area for designated TETD.)



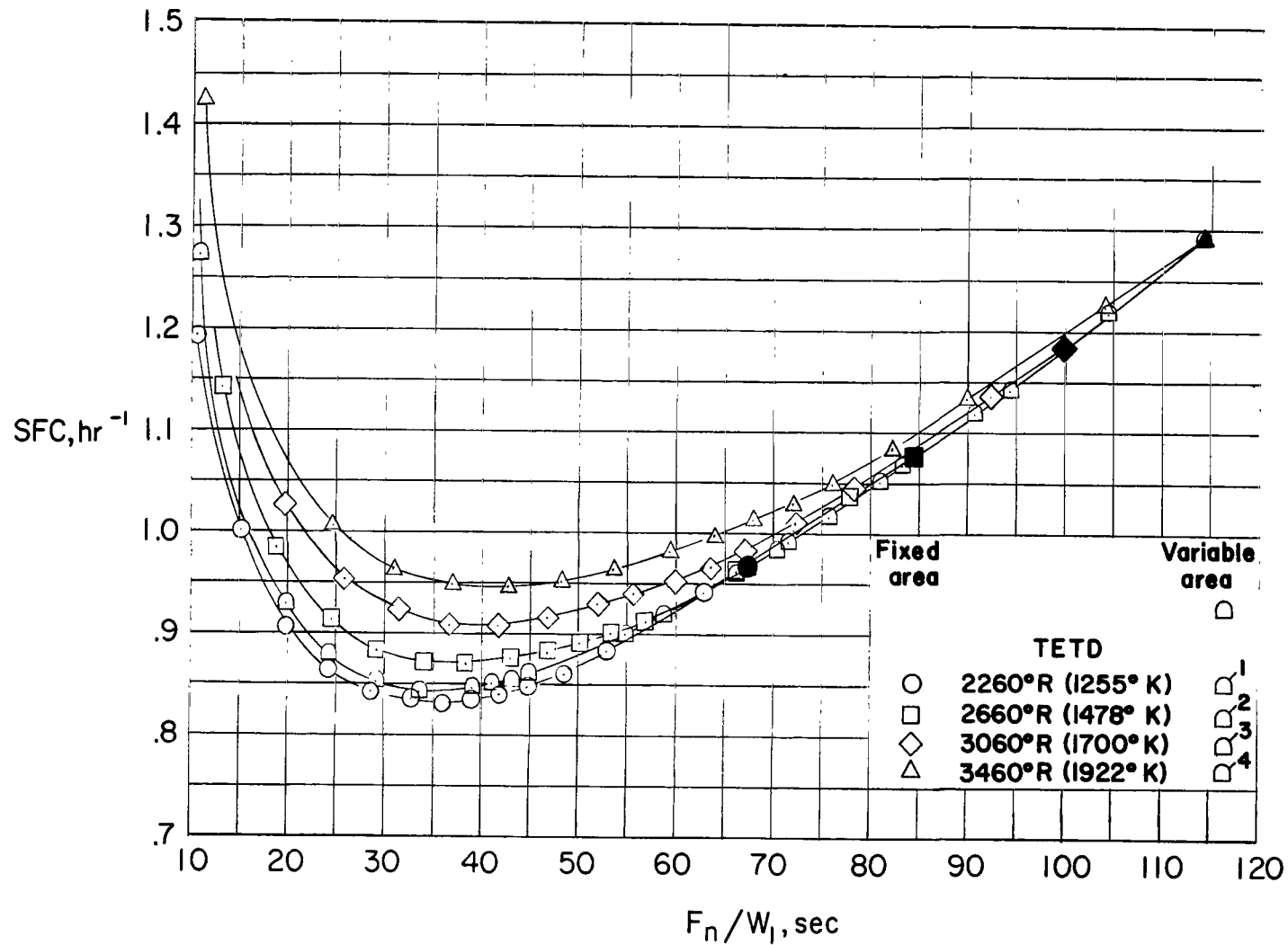
(b) $M = 0.4$; Altitude = 15 000 ft (4572 m).

Figure 11.- Continued.



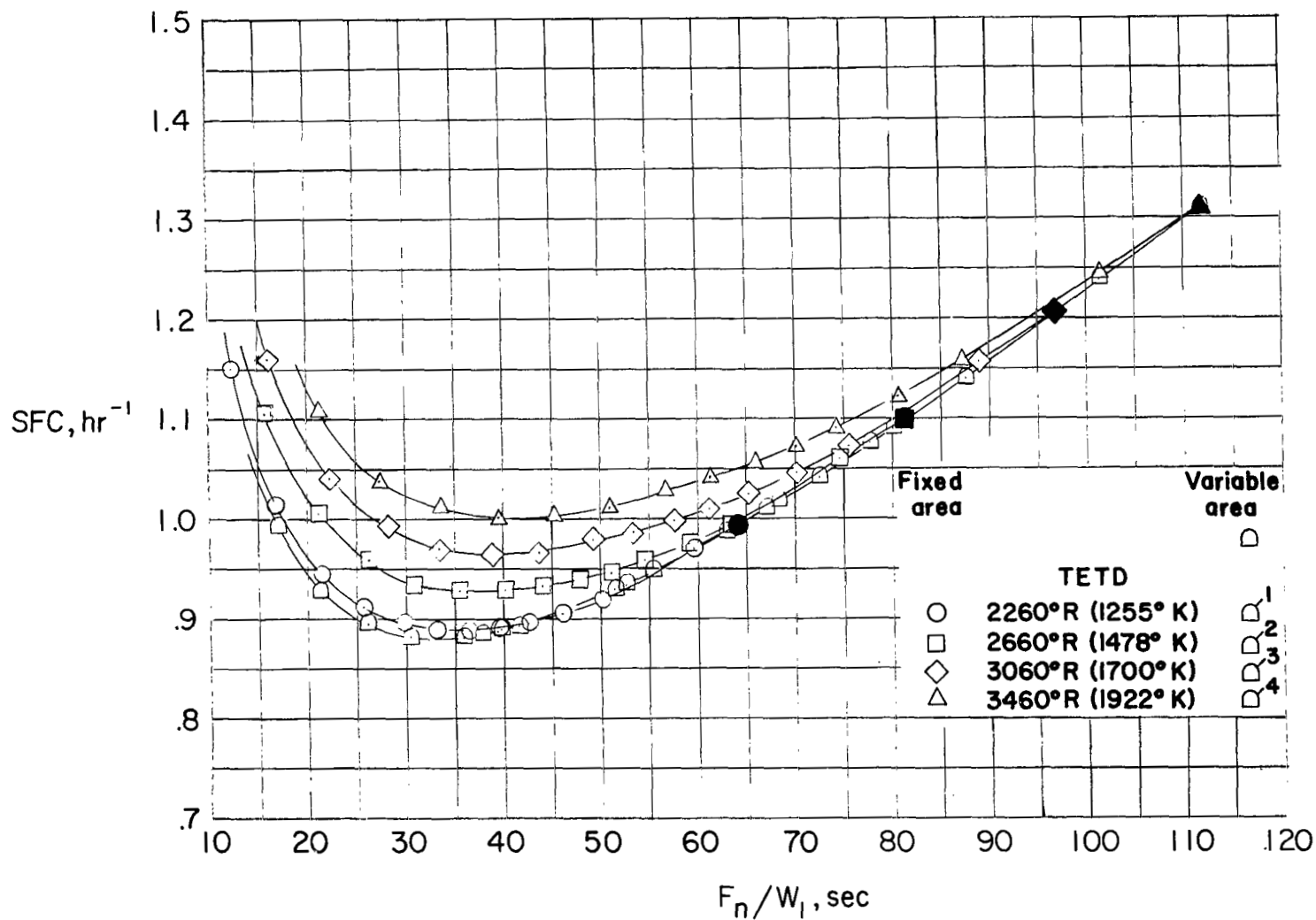
(c) $M = 0.6$; Altitude = 25 000 ft (7620 m).

Figure 11.- Continued.



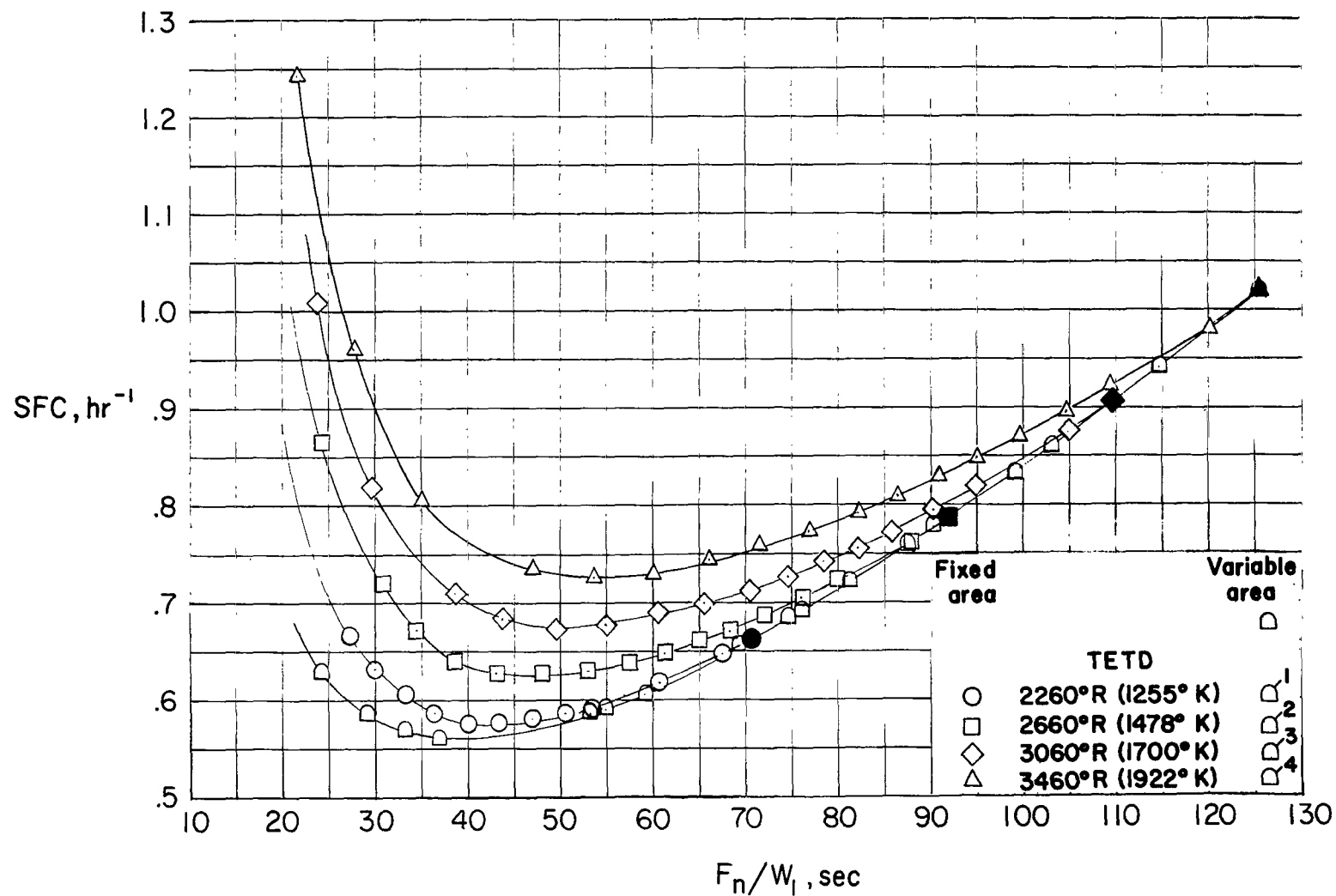
(d) $M = 0.8$; altitude, stratosphere.

Figure 11.- Continued.



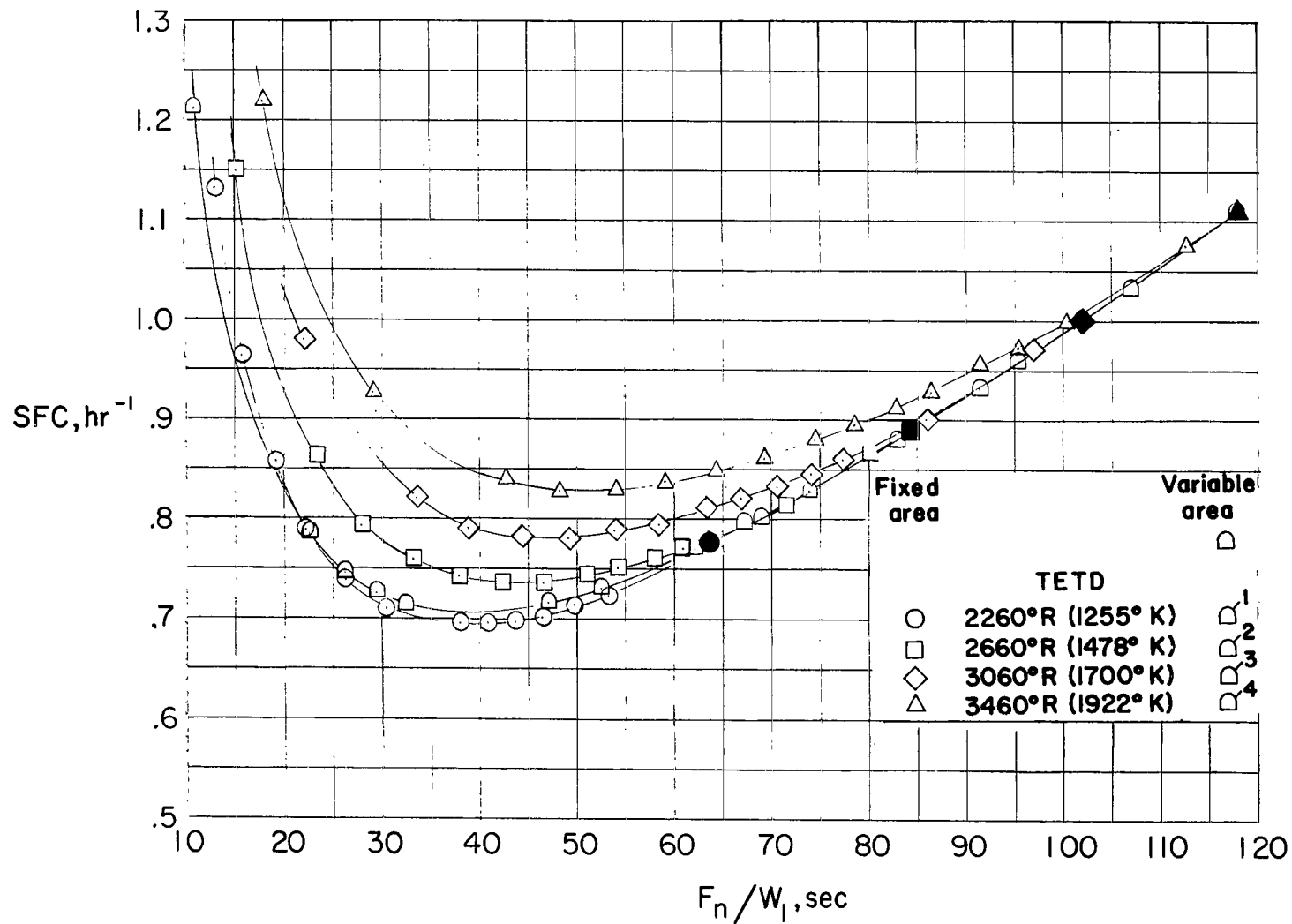
(e) $M = 1.0$; altitude, stratosphere.

Figure 11.- Concluded.



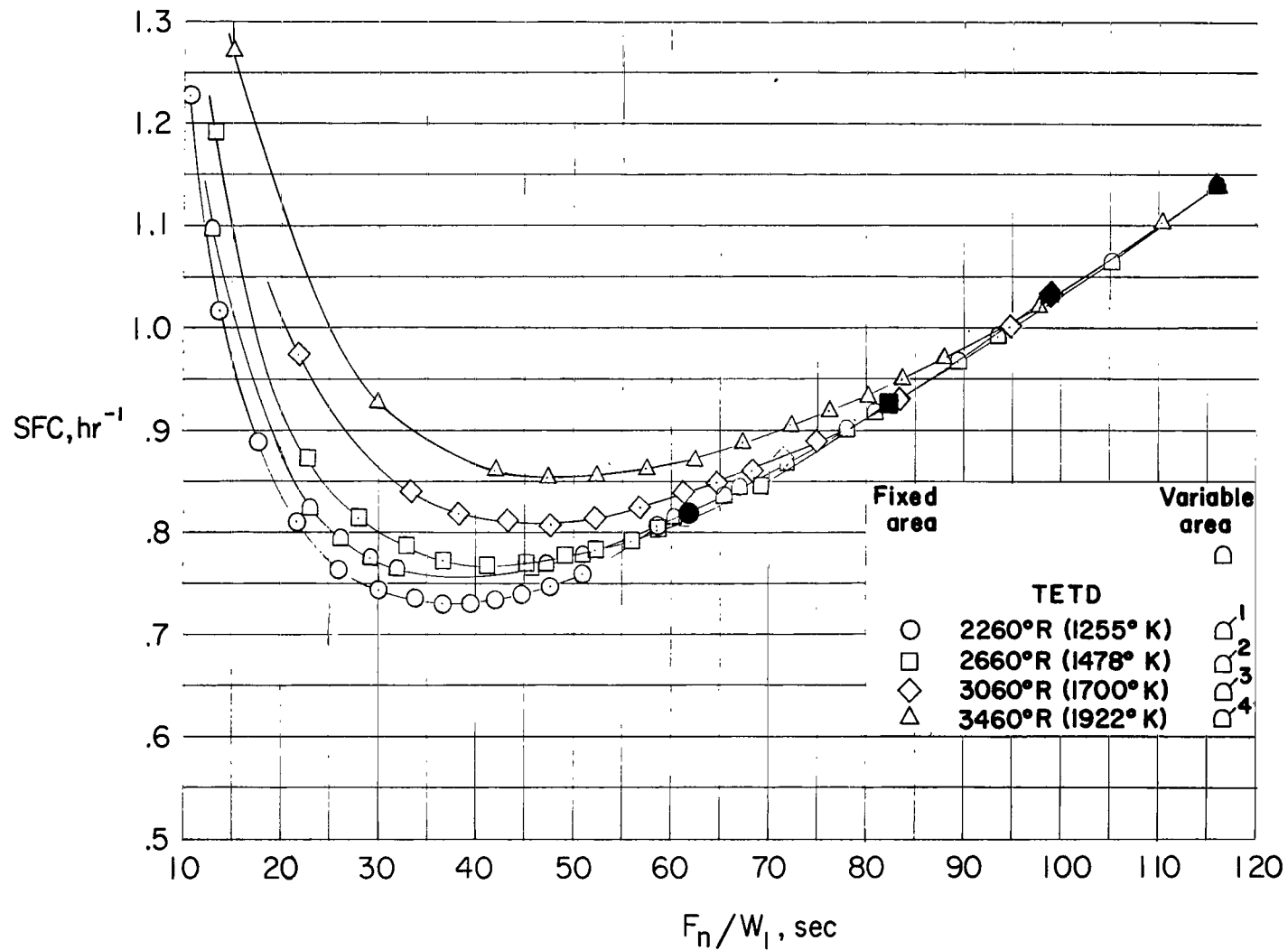
(a) $M = 0$; Altitude = 0.

Figure 12.- Specific performance of engines with CPRD of 30 at partial-power operation. (Solid symbols indicate maximum power. Numbers on symbols indicate 40-percent reduction in turbine area for designated TETD.)



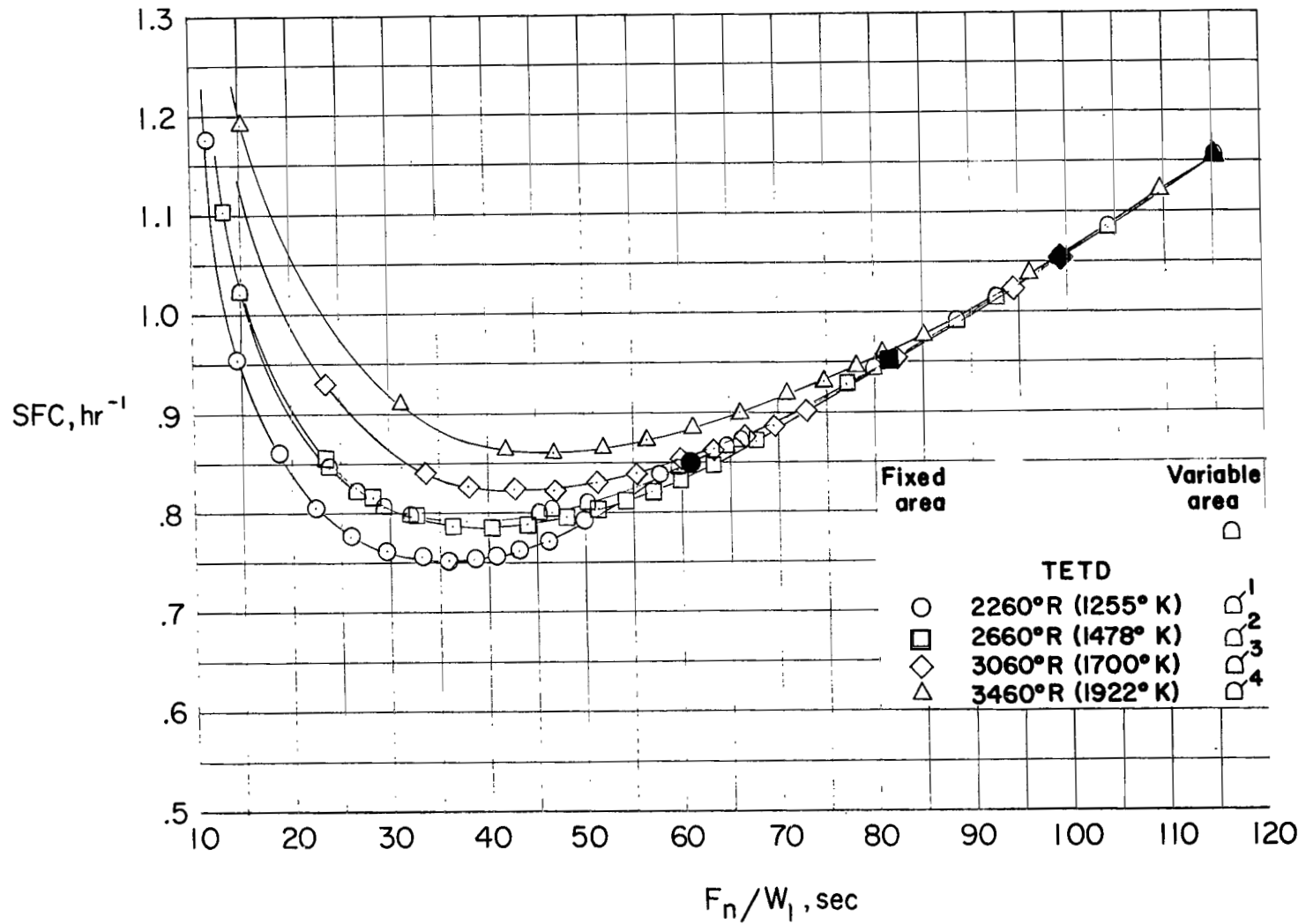
(b) $M = 0.4$; Altitude = 15 000 ft (4572 m).

Figure 12.7 Continued.



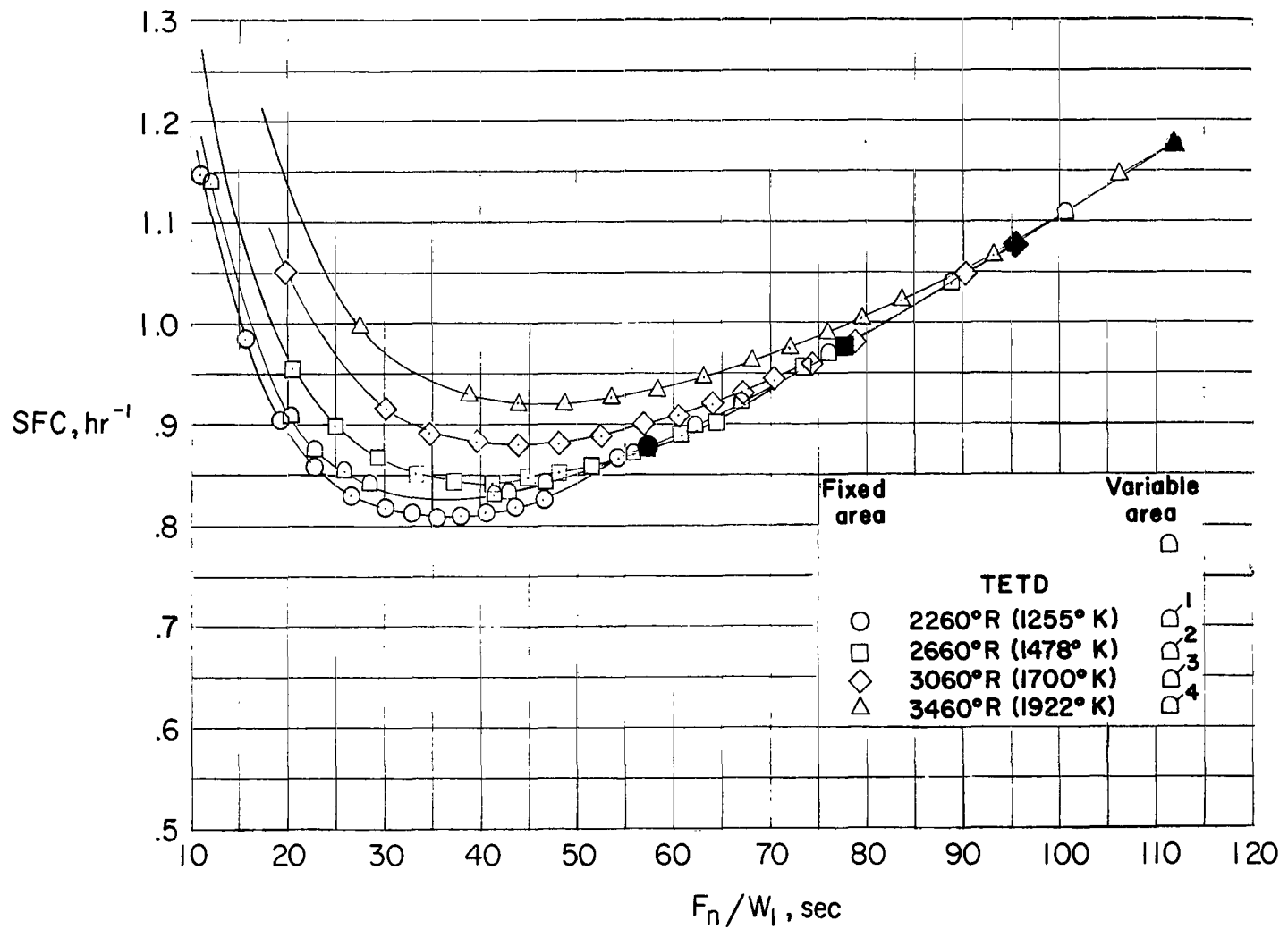
(c) $M = 0.6$; Altitude = 25 000 ft (7620 m).

Figure 12.- Continued.



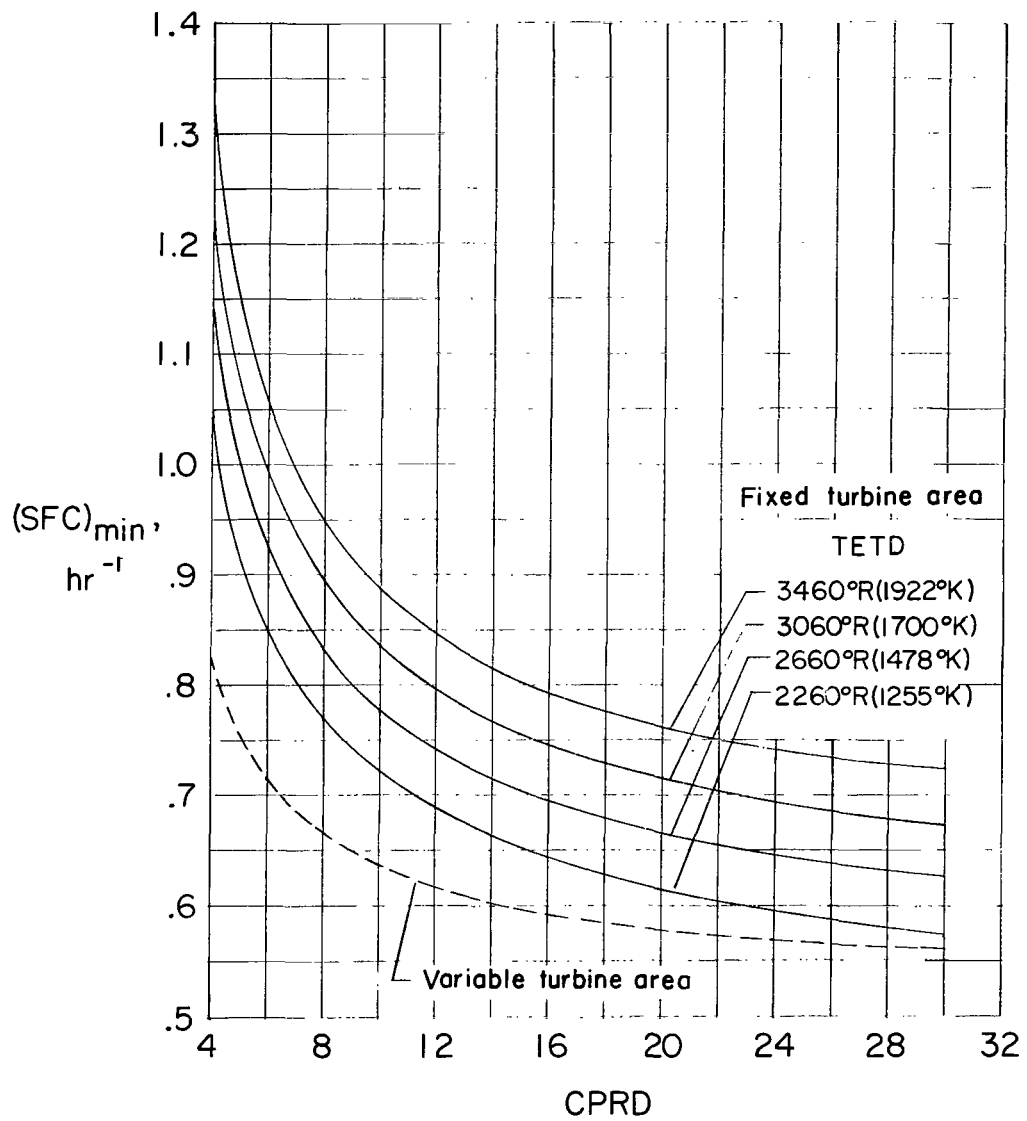
(d) $M = 0.8$; altitude, stratosphere.

Figure 12.- Continued.



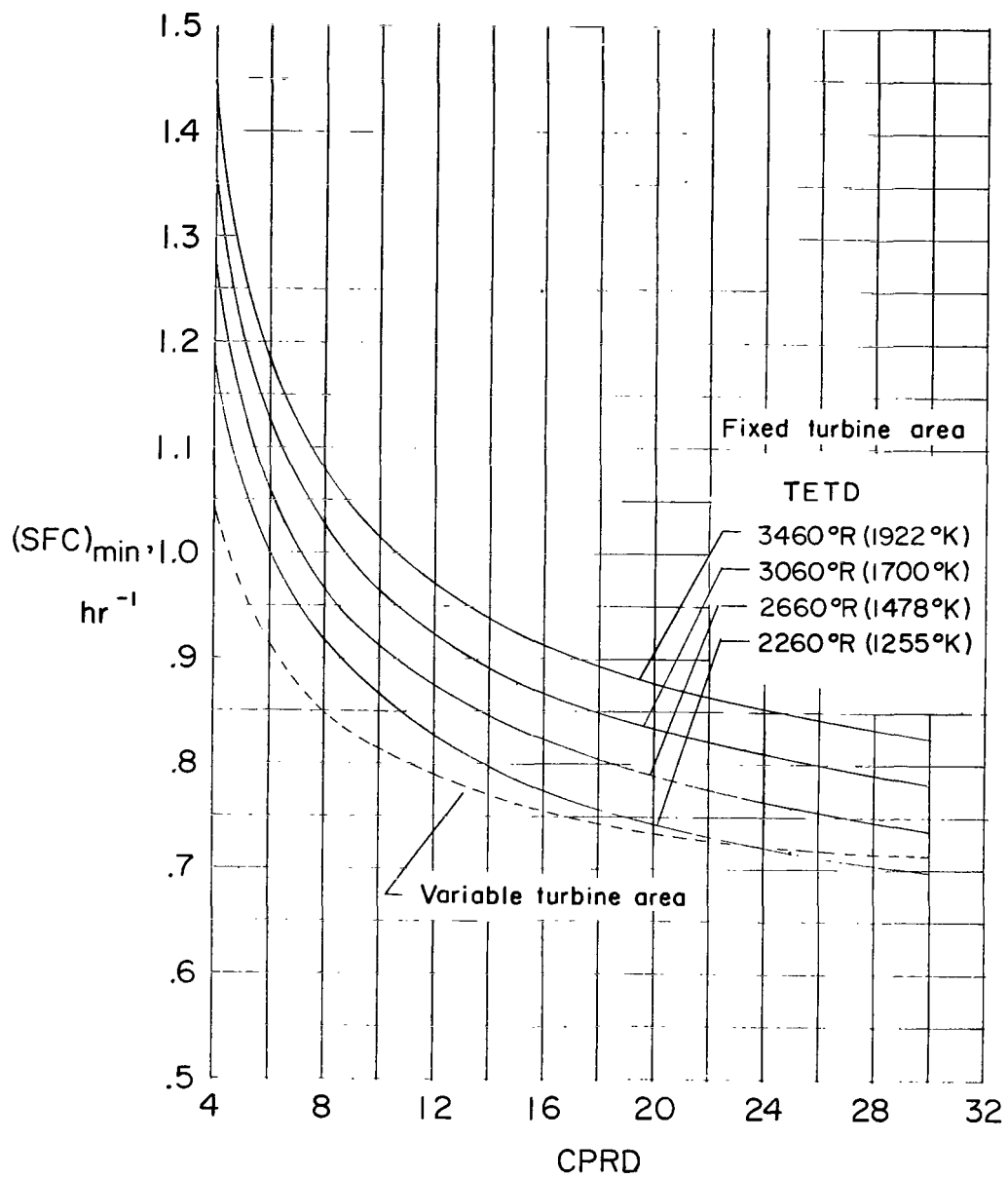
(e) $M = 1.0$; altitude, stratosphere.

Figure 12.- Concluded.



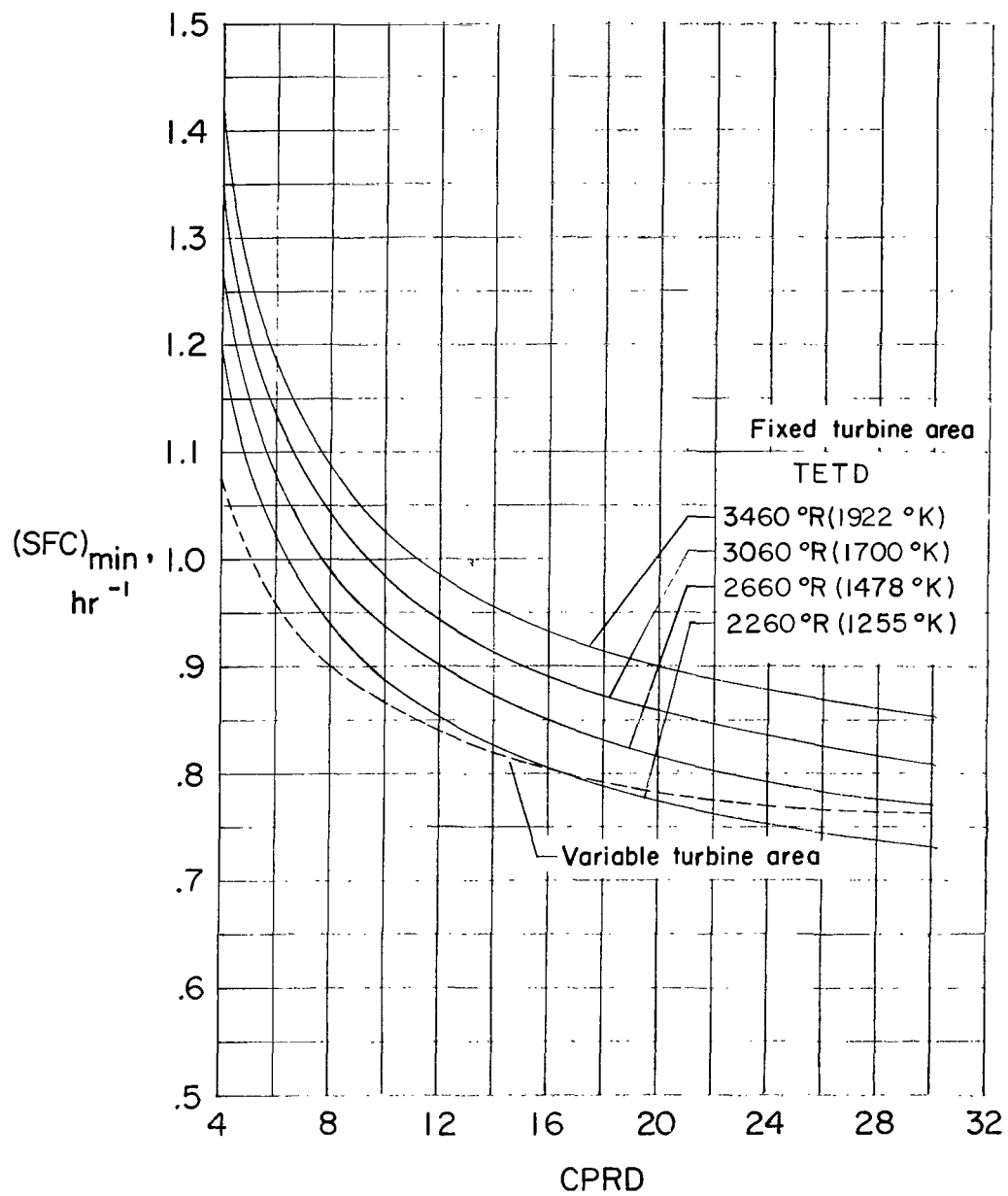
(a) $M = 0$; Altitude = 0.

Figure 13.- Correlation of partial-power minimum SFC for engines with fixed and variable turbine areas.



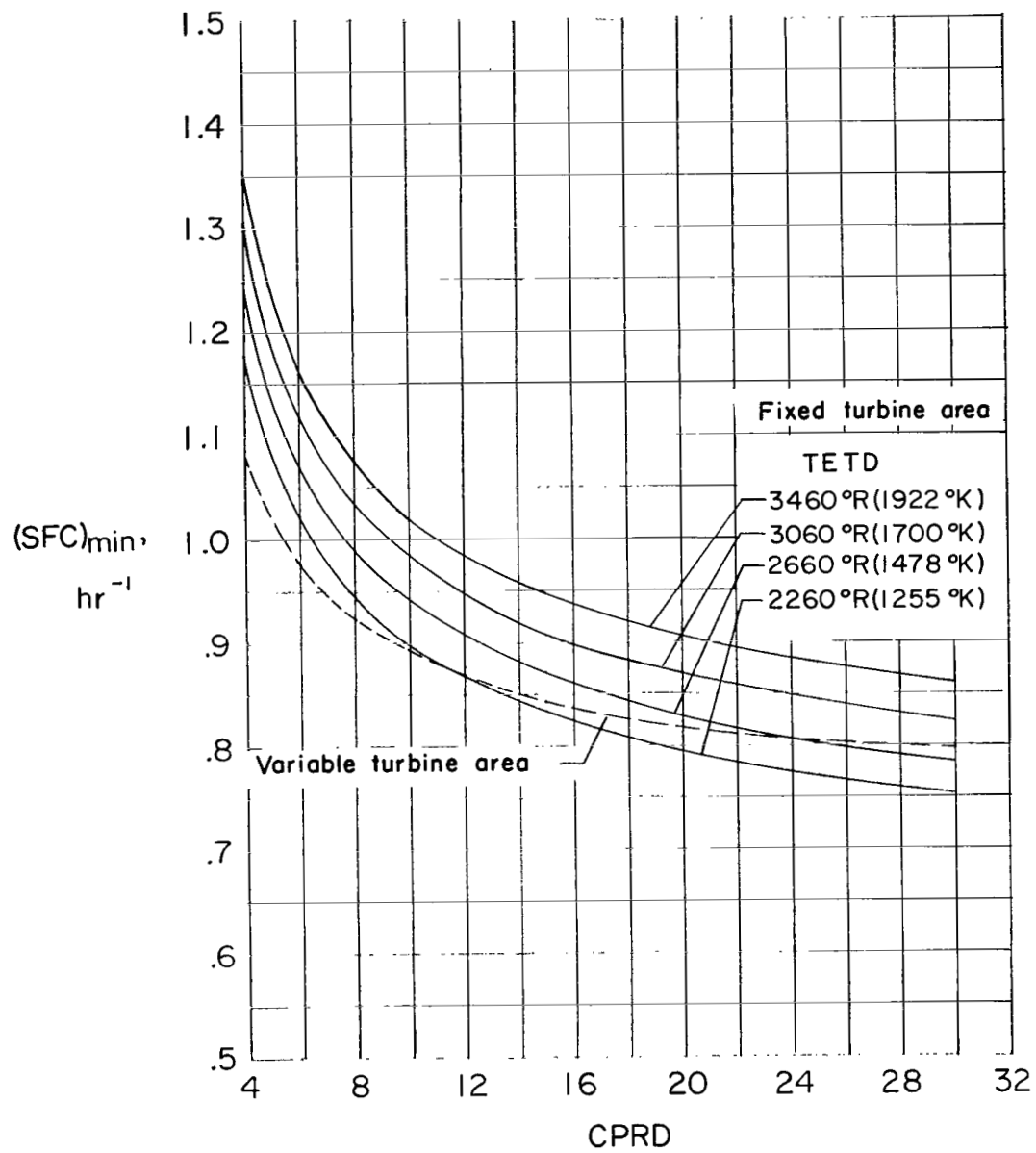
(b) $M = 0.4$; Altitude = 15 000 ft (4572 m).

Figure 13.- Continued.



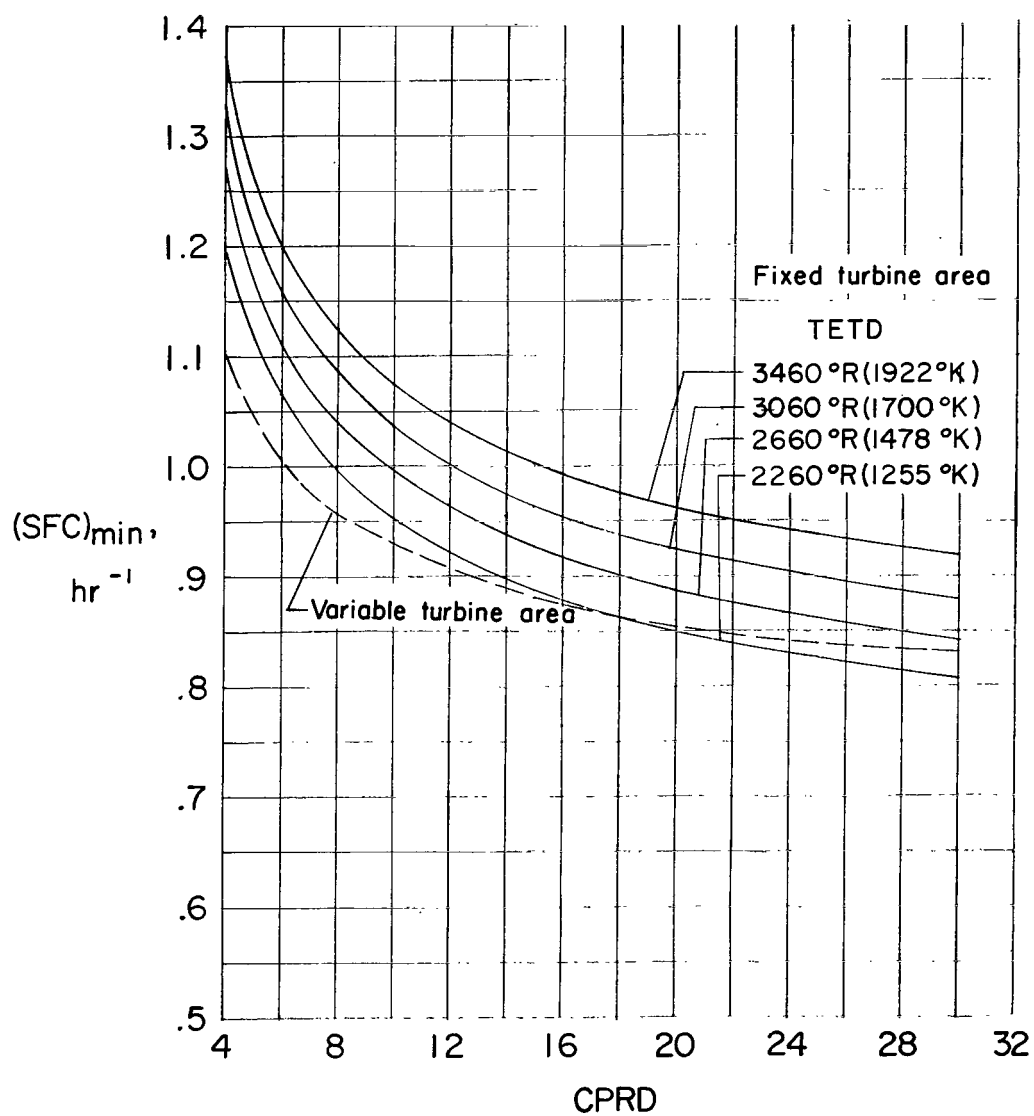
(c) $M = 0.6$; Altitude = 25 000 ft (7620 m).

Figure 13.- Continued.



(d) $M = 0.8$; altitude, stratosphere.

Figure 13.- Continued.



(e) $M = 1.0$; altitude, stratosphere.

Figure 13.- Concluded.

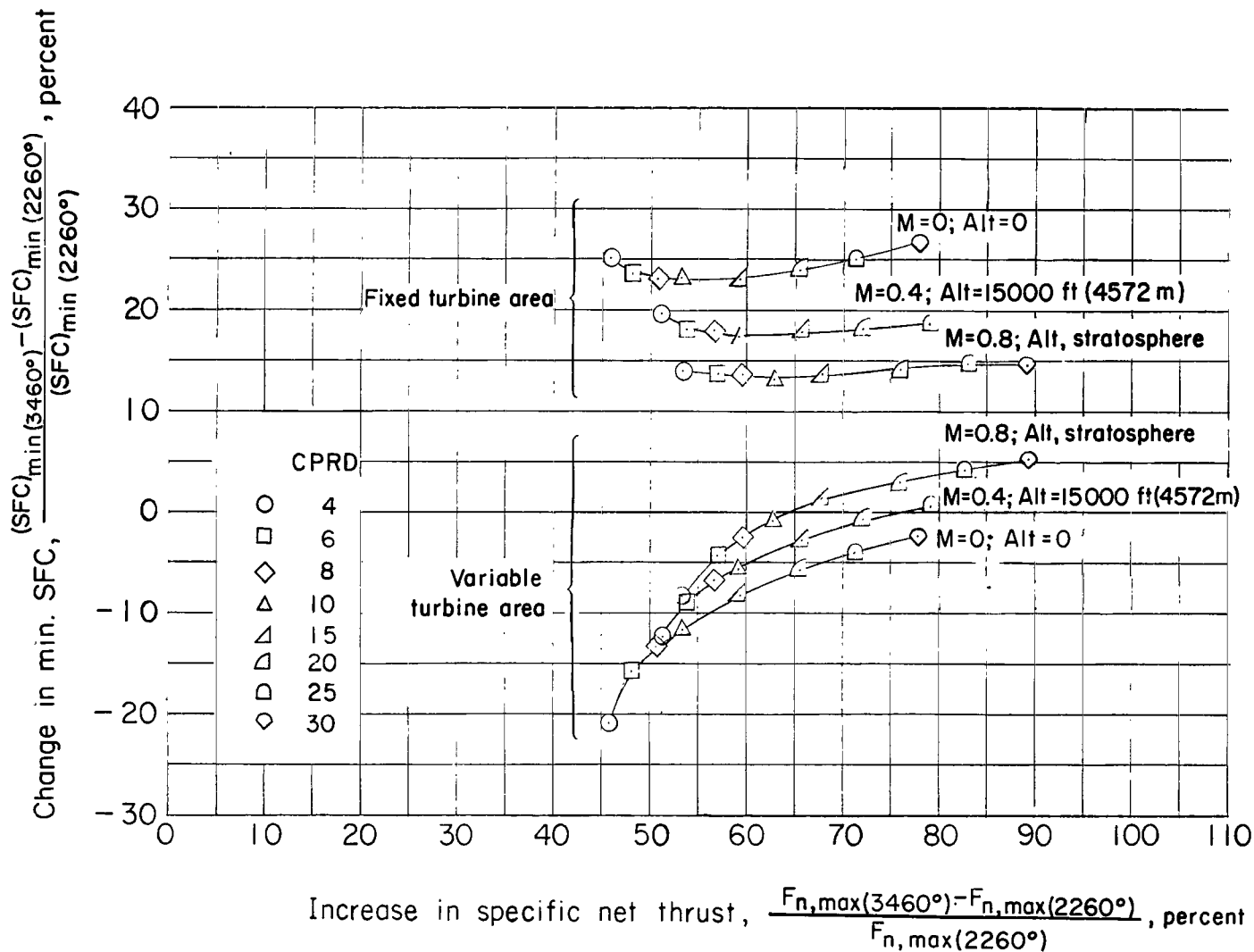
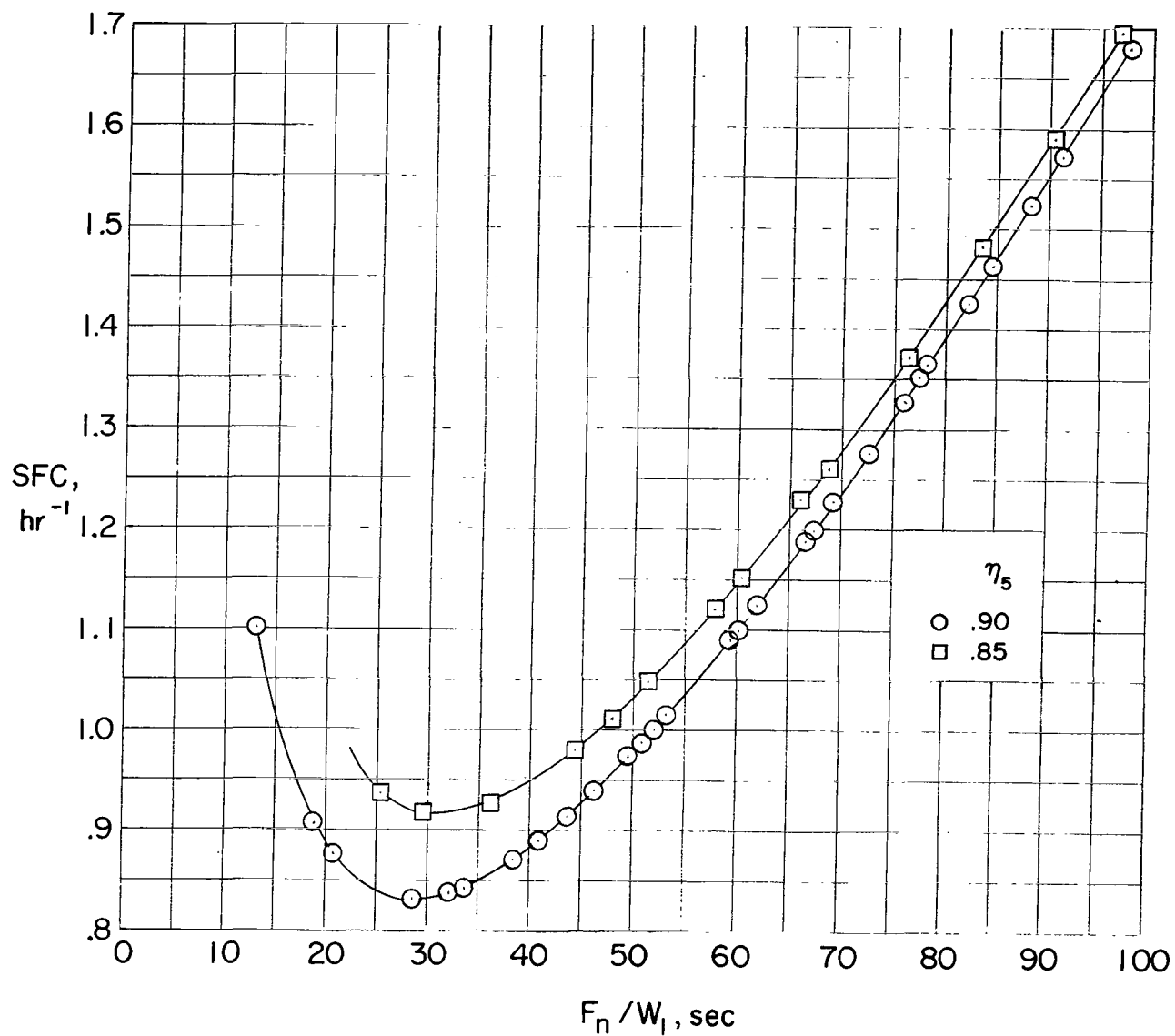
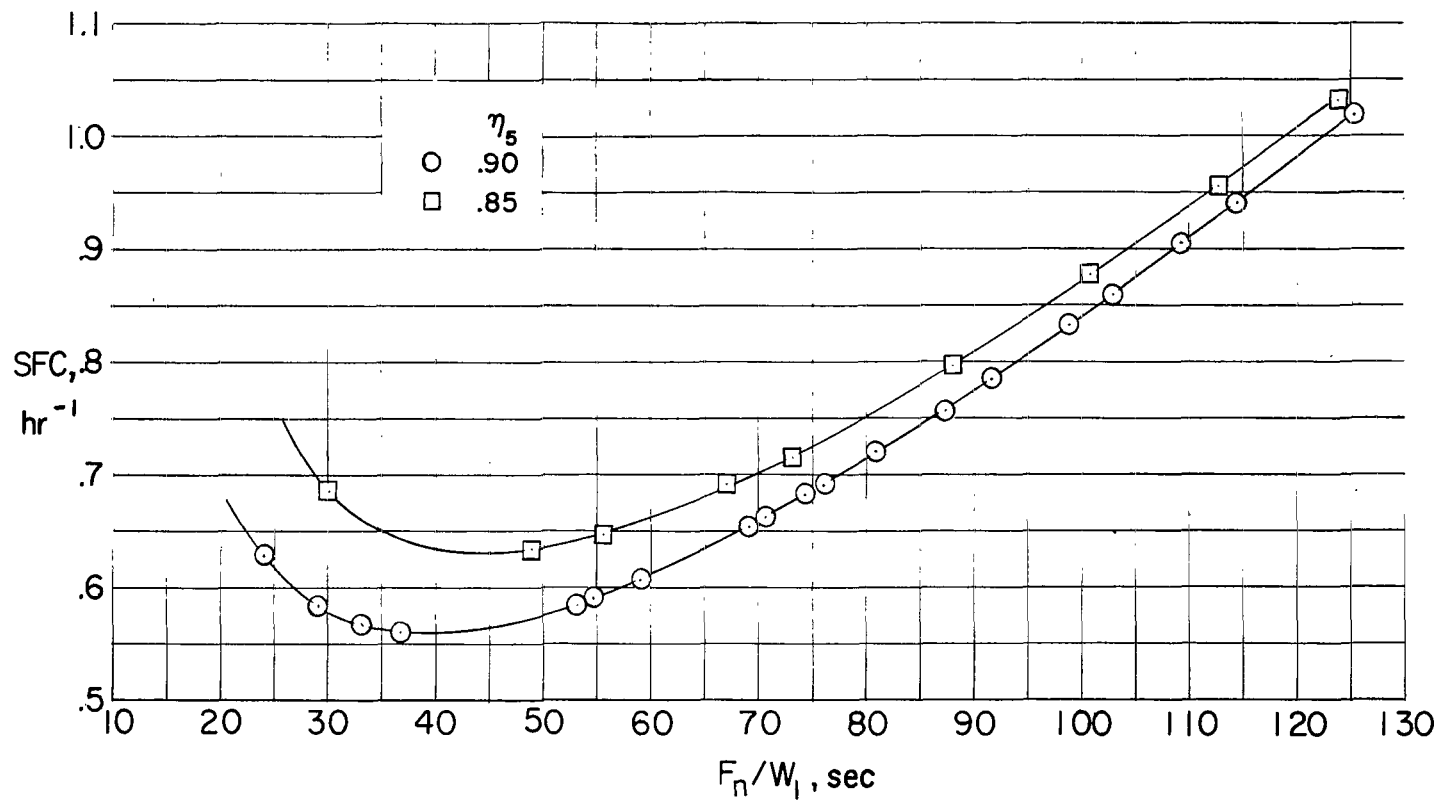


Figure 14.- Effects of increase in maximum TETD from 2260° R (1255° K) to 3460° R (1922° K) on change in maximum specific thrust and minimum SFC for engines with fixed and variable turbine area.



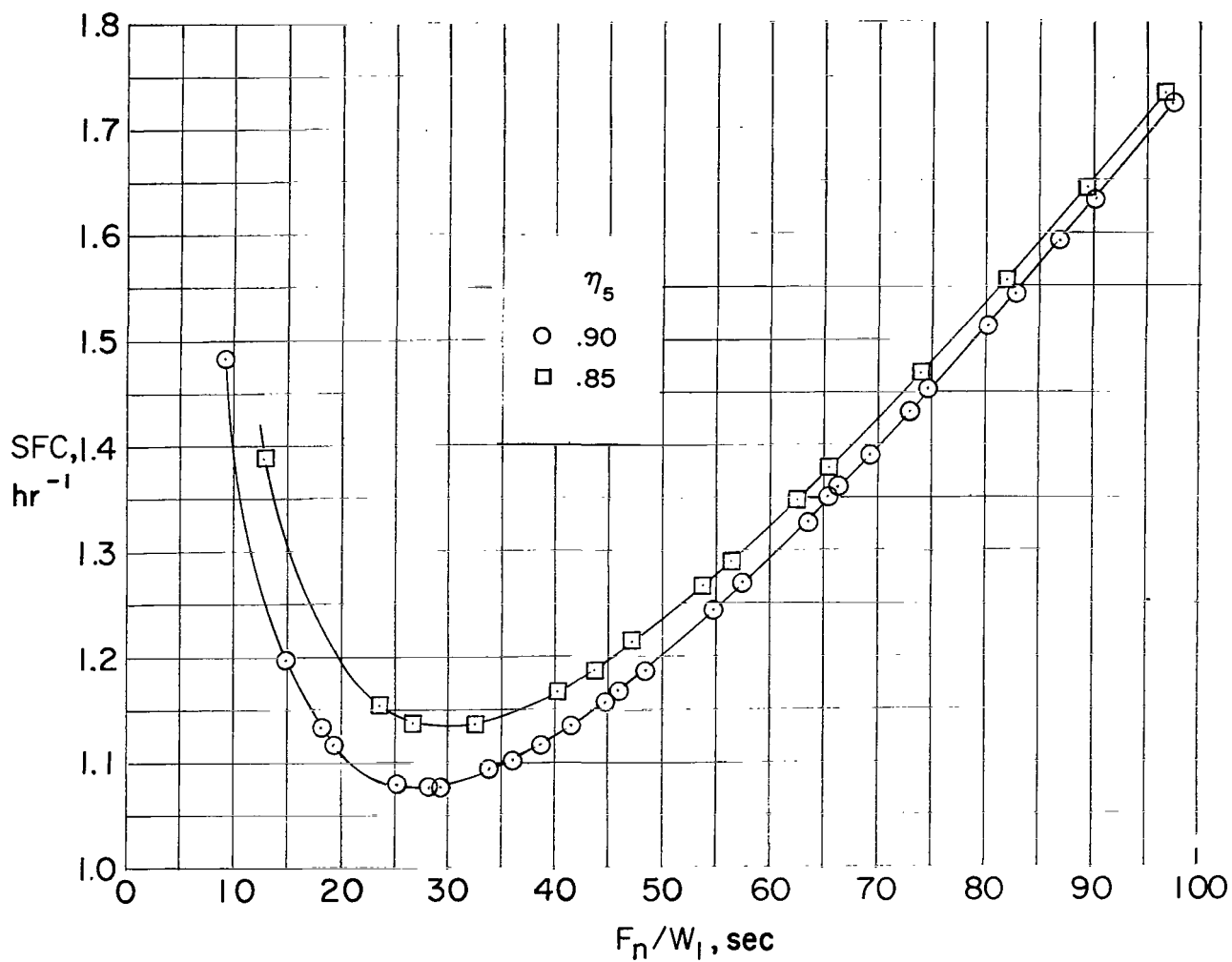
(a) CPRD = 4; $M = 0$; Altitude = 0.

Figure 15.- Effects of variation of turbine polytropic efficiency on performance of engines with variable turbine area.



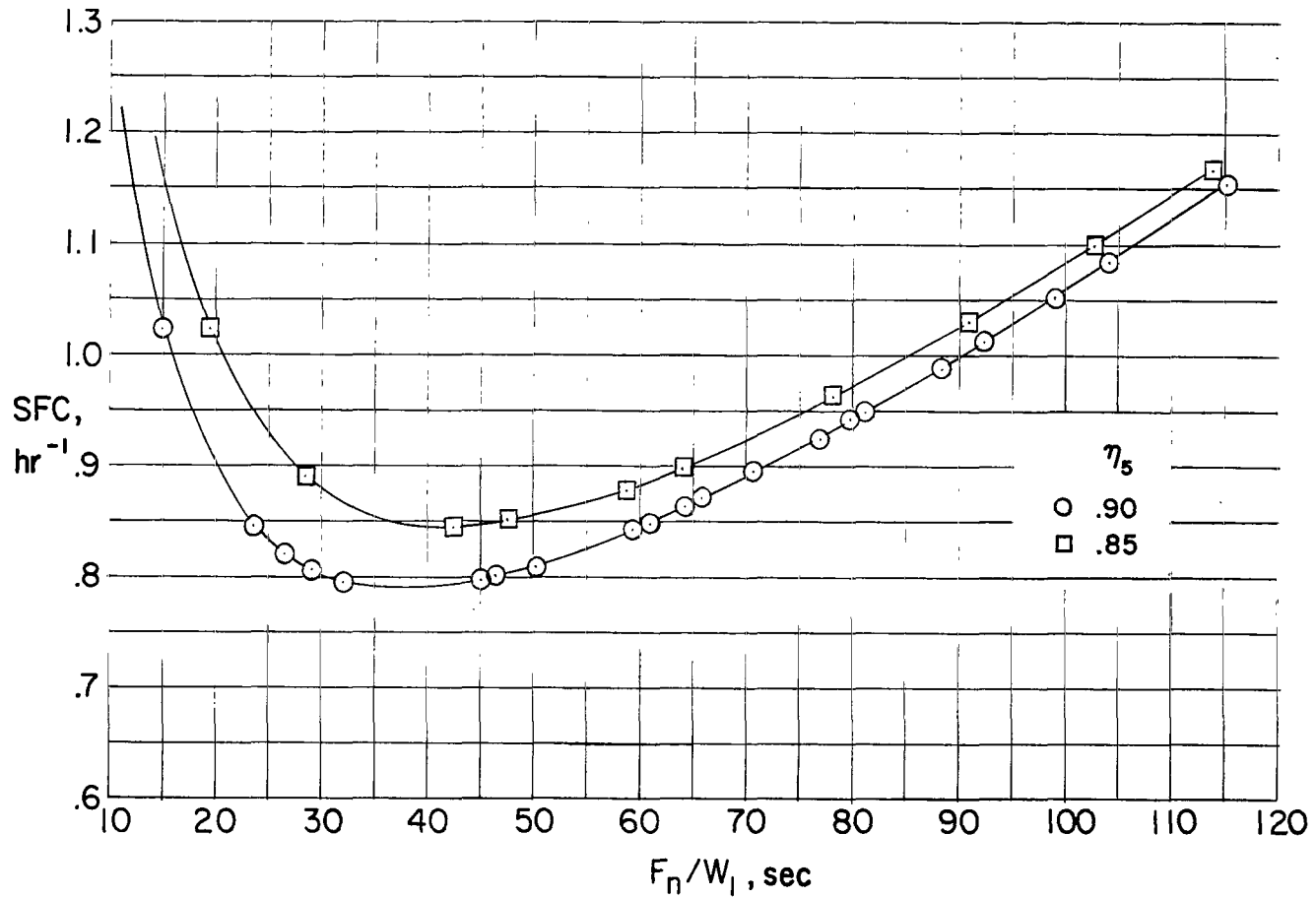
(b) CPRD = 30; M = 0; Altitude = 0.

Figure 15.- Continued.



(c) CPRD = 4; M = 0.8; altitude, stratosphere.

Figure 15.- Continued.



(d) CPRD = 30; M = 0.8; altitude, stratosphere.

Figure 15.- Concluded.

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